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Digital Image Colorimetry for Natural Dye and Pigment Color Quantification: A Systematic Review

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Abstract: *Accurate color measurement is essential across analytical chemistry, food science, and textile technology, yet conventional spectrophotometers remain costly and inaccessible for many researchers. Digital Image Colorimetry (DIC) is a low-cost alternative that quantifies color from digital cameras, scanners, or smartphones using RGB or CIELAB values. This Systematic Literature Review followed the PRISMA 2020 guideline to map DIC applications on natural dyes and pigments. Literature published between 2016 and 2026 was retrieved from Scopus; of 107 initial records, 44 articles met the inclusion criteria after document-type and year filtering followed by title and abstract screening. DIC applications were dominated by chemical sensing (45%) and plant phenotyping (39%), followed by food packaging (11%), while textile dyeing accounted for only 4.5% (2 articles). In chemical sensing, 9 of 11 studies reporting correlation coefficients showed values above 0.99 against conventional methods. The review concludes that DIC is a validated method in the dominant domains but remains underutilized for natural dye-based textile color evaluation, warranting further investigation. Its low-cost, smartphone-based nature also suggests potential for participatory chemistry education.*

Keywords: *digital image colorimetry; natural dye; RGB analysis; textile dyeing; systematic review*

INTRODUCTION

Accurate color measurement is a fundamental requirement across analytical chemistry, food science, and textile technology. Conventional instruments such as spectrophotometers and colorimeters have long served as the standard for color quantification due to their high accuracy and precision. However, these instruments are generally expensive, non-portable, and require specific technical expertise, making them difficult to access for researchers and educators with limited resources (Caraballo et al., 2021).

Digital Image Colorimetry (DIC) has emerged as an alternative method that utilizes digital cameras, scanners, or smartphone cameras to capture an image of an object, followed by color value analysis using image-processing software (Wongthanyakram et al., 2019). This approach offers considerable advantages in terms of cost, accessibility, and portability compared to conventional instruments. Parallel to this trend, chemistry education research has also increasingly

adopted low-cost digital technologies, such as mobile-based augmented reality applications (Ritonga & Nurfajriani, 2026) and freely accessible simulation tools (Nafillah et al., 2026), to improve accessibility and engagement in chemistry learning.

Natural dyes and pigments derived from plants, such as curcumin, anthocyanin, and carotenoids, have gained increasing attention as environmentally friendly alternatives to synthetic dyes, both in textile dyeing and as colorimetric sensing agents. DIC has been applied to these pigments in several research domains and frequently shows high correlation with conventional spectrophotometric methods (Choodum et al., 2020; Wongthanyakram et al., 2019).

Despite this growing body of evidence, DIC applications remain concentrated in chemical sensing and plant phenotyping, while its use for natural dye-based textile color evaluation is still scarce, with only isolated studies addressing this domain directly (Batarius et al., 2022; Nateri et al., 2019). While DIC has been validated in chemical sensing and plant phenotyping, no systematic review has mapped its distribution across domains, particularly in textile dyeing, leaving the scale of this imbalance unclear.

This study addresses that gap by conducting a systematic literature review that maps DIC applications on natural dyes and pigments across all research domains. It quantifies the distribution of application areas and evaluates the reported validity of DIC against conventional methods. Accordingly, this study aims to systematically review the application domains, methodological characteristics, and validity of DIC for natural dyes and pigments in literature published between 2016 and 2026, and to identify research gaps that may guide future studies, particularly in textile dyeing and science education. This review addresses three research questions: (RQ1) What are the dominant application domains of DIC on natural dyes and pigments? (RQ2) How valid is DIC compared with conventional methods? (RQ3) What research gaps exist, particularly in textile dyeing and chemistry education?.

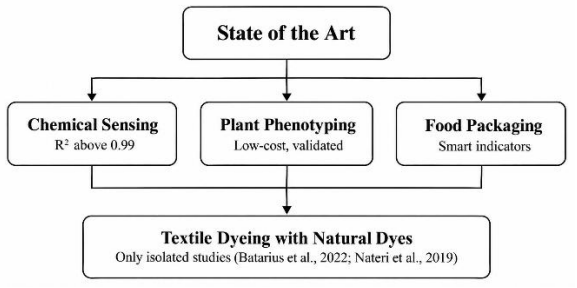


Figure 1. State of the art of DIC applications on natural dyes and pigments.

LITERATURE REVIEW

Digital Image Colorimetry (DIC) is grounded in the principle that color information captured through a digital image, typically represented in RGB (Red, Green, Blue) or converted to CIELAB color space, can be correlated with the concentration or intensity of a colored analyte or pigment. This principle has been widely validated across multiple domains over the past decade, with correlation coefficients (R^2) frequently exceeding 0.99 when compared against conventional spectrophotometric methods (Choodum et al., 2020; Wongthanyakram et al., 2019).

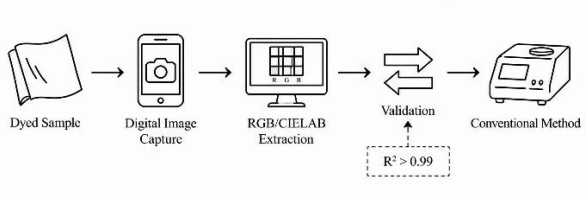


Figure 2. General conceptual workflow of Digital Image Colorimetry (DIC).

Within the chemical sensing domain, curcumin has emerged as one of the most extensively studied natural pigments for DIC-based applications, owing to its pH sensitivity and strong colorimetric response to various analytes. Nandini et al. (2026) developed a curcumin-based smartphone colorimetric sensor for detecting H_2O and D_2O, while Ismail et al. (2024) applied a similar approach for the quantification of total curcuminoids in food samples. Beyond curcumin, other natural pigments such as catechin have also been incorporated into DIC-based sensing platforms, as demonstrated by

Phatthanawiwat et al. (2022) in the detection of iron using catechin- and curcumin-immobilized starch cryogels.

In the plant phenotyping domain, DIC has been employed as a low-cost alternative to conventional pigment extraction and chemical assays for estimating carotenoid, chlorophyll, and anthocyanin content. de Carvalho et al., (2022) applied image-based phenotyping to predict carotenoid content in cassava roots, while Suchowilska et al. (2022) used digital image analysis to characterize color and shape descriptors of wheat genotypes. These studies consistently report that DIC-derived color parameters correlate significantly with laboratory-based pigment quantification, supporting its viability as a rapid, non-destructive screening tool.

DIC has also been applied in the development of smart food packaging, where natural pigments such as anthocyanin serve as visual freshness indicators Zhang et al., (2026) developed a blueberry anthocyanin-functionalized hydrogel label for smartphone-assisted freshness monitoring of perishable proteins, while Bao et al. (2024) demonstrated a similar application using a 3D-printed colorimetric film. In these studies, DIC functions not merely as a measurement tool but as an integral component of the sensing mechanism itself, where color change is captured and interpreted directly through a smartphone camera.

In contrast to these well-established domains, the application of DIC to textile dyeing using natural dyes remains comparatively underexplored. Batarius et al. (2022) applied MSE and PSNR parameters derived from digital images to assess the color degradation of naturally dyed woven fabric under sunlight exposure, while Nateri et al. (2019) compared scanner-based digital imaging against spectrophotometric measurement for madder-dyed nylon fabric, reporting comparable results between the two methods. Although both studies suggest that DIC holds methodological promise for textile applications, the limited number of studies addressing this domain indicates that its potential remains largely untested at scale.

Taken together, the literature shows that DIC is methodologically mature in chemical sensing, plant phenotyping, and food packaging, whereas its distribution across domains and its translation into textile applications have not been systematically examined.

METHODS

Research Design

This study employed a Systematic Literature Review (SLR) design guided by the PRISMA 2020 framework (Page et al., 2021), which provides a transparent and reproducible protocol for identifying, screening, and synthesizing scientific literature. This design was selected because the objective of the study was not to generate new experimental data, but to systematically map and synthesize existing evidence on the application of Digital Image Colorimetry (DIC) on natural dyes and pigments.

Data Source and Search Strategy

Literature was retrieved from the Scopus database on 12 June 2026. The search string applied to titles, abstracts, and keywords (TITLE-ABS-KEY) was: ("digital image colorimetry" OR "digital image analysis" OR "RGB analysis" OR "smartphone colorimetry") AND ("natural dye" OR "natural pigment" OR anthocyanin OR carotenoid OR curcumin). The search was limited to journal articles published between 2016 and 2026.

Eligibility Criteria

Studies were included if they met the following criteria: (1) peer-reviewed journal articles published between 2016 and 2026; (2) written in English; (3) explicitly applied or tested a DIC-based method for color quantification; and (4) involved a natural dye or pigment as the object of color measurement. Studies were excluded if they: (1) did not explicitly describe a digital-image-based color measurement method; (2) relied solely on conventional methods without any

DIC component; (3) did not involve a natural dye or pigment; or (4) were conference papers, non-systematic reviews, or duplicate publications.

Study Selection

The initial search yielded 107 records. After filtering by document type and publication year, 87 records remained for title and abstract screening. Due to limited institutional access to subscription-based databases, full-text screening could not be performed for the entire set of records; screening was therefore based primarily on title and abstract content. For studies whose data are cited specifically in this review, particularly those addressing textile-related applications, cross-verification was performed against open-access secondary sources to confirm data accuracy. Following this process, 44 articles met all eligibility criteria and were included in the final synthesis. The complete selection process is presented in Figure 3.

Data Extraction and Synthesis

Data were extracted from each included article using a standardized table with the following fields: application domain, type of natural dye or pigment, DIC method and device, comparison method (where reported), and reported validity outcome. Validity outcomes were recorded as stated in the primary studies (correlation coefficient R^2 or r, limit of detection, or statistical equivalence with a reference method) without recalculation, and no minimum threshold was applied for inclusion. Each article was assigned to a single application domain according to the primary purpose of the color measurement: chemical sensing (natural pigment used as a sensing agent for an analyte), plant phenotyping (pigment content or color traits of plant or food material), food packaging (pigment-based freshness indicator), or textile dyeing (natural dye applied to fabric). Thematic clustering of the extracted descriptions was assisted by Claude and was used only to group the extracted information into themes; study selection, data extraction, domain classification, and interpretation were conducted manually by the author.

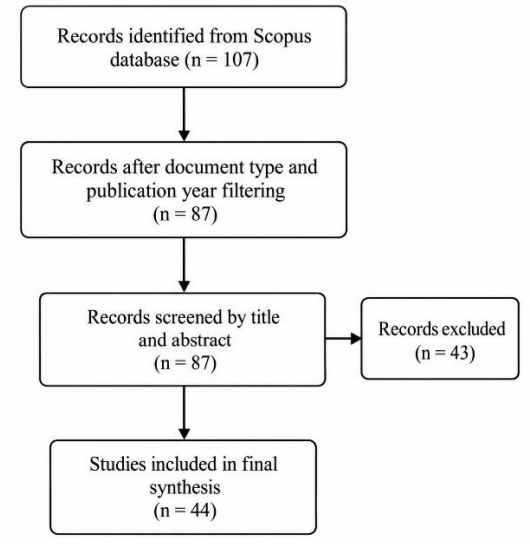


Figure 3. PRISMA flow diagram of the article selection process.

RESULT AND DISCUSSION

Overview of Included Studies

Following the selection process described in Figure 3, 44 articles met all eligibility criteria and were included in this review. The included studies originate from a wide range of application contexts, published in journals spanning analytical chemistry, food science, agricultural science, and materials science. A concise summary of the characteristics of these 44 studies, including their application domain, specific DIC method, and reported validity outcomes, is presented in Table 1.

Table 1. Summary of study characteristics, including application domain, DIC method, and reported validity outcomes (n = 44).

No	Domain	DIC Method	Validity Result	Author & Year
1	Chemical Sensing	Smartphone RGB	LOD 0.327-0.019%	(Nandini et al., 2026)
2	Plant Phenotyping	Computer image (CIELAB/RGB/HSB)	Correlated with carotenoid content in feed	(Zantioti & Malandrakis, 2026)
3	Food Packaging	Smartphone RGB	Good correlation with	(Zhang et al., 2026)

			TVB-N/pH	
4	Food Packaging	Camera-readable colorimetric	Significant <10% CO2	(Sonawane et al., 2026)
5	Plant Phenotyping	DIA (CIELAB, GrainScan)	4 differentiated color groups	(Zykin et al., 2025)
6	Chemical Sensing	DIC	R2 = 0.9981 vs UV-Vis 0.9982	(Shabrina et al., 2025)
7	Plant Phenotyping	Image analysis+ML	R2 0.573-0.818	(Agarwal et al., 2025)
8	Chemical Sensing	Smartphone RGB	LOD 2.93 mg/L	(Chinnawat et al., 2025)
9	Chemical Sensing	Smartphone DIC	R2 > 0.9906	(Alikord et al., 2025)
10	Chemical Sensing	Colorimetric sensor RGB	R2 > 0.9 (chlorophyll)	(Lorenzo et al., 2025)
11	Food Packaging	Smartphone RGB	Ammonia sensitivity 35.43%	(Bao et al., 2024)
12	Chemical Sensing	Smartphone DIC	Equivalent to HPLC (P=0.05)	(Jantra et al., 2024)
13	Chemical Sensing	RGB analysis	R2 = 0.9903	(Eskandari et al., 2024)
14	Chemical Sensing	Smartphone DIC	LOD 0.02 µg/mL, R2 > 0.9965	(Ismail et al., 2024)
15	Food Packaging	Smartphone RGB	Correlated with G/R freshness ratio	(Dong et al., 2023)
16	Chemical Sensing	DIA (RGB channel R)	Equivalent to GC-FID	(Caleja-Ballesteros & Ballesteros, 2023)
17	Chemical Sensing	DIC (RGB smartphone)	Good linear calibration	(Wirojsaengthong et al., 2023)
18	Chemical Sensing	Digital-image photometry	r ≥ 0.997 vs spectrophotometry	(Claudio Martins et al., 2023)
19	Chemical Sensing	Smartphone DIC+ImageJ	R2 > 0.9955	(Caleb et al., 2023)
20	Plant Phenotyping	DIA+ML (CNN)	Accuracy 0.821	(Komyshev et al., 2023)
21	Chemical Sensing	DIC	Response time <1 minute	(Matthew et al., 2022)
22	Textile	MSE/PSNR+RGB	RGB change of 8-10%	(Batarius et al., 2022)
23	Food Packaging	Smartphone RGB	-	(Li et al., 2022)
24	Chemical Sensing	DIC	R2 > 0.9997 vs FAAS	(Phatthanawiwat et al., 2022)
25	Plant Phenotyping	DIA (color descriptors)	Correlated with processing quality	(Suchowilska et al., 2022)
26	Plant Phenotyping	DIC (digital camera)	CIELAB parameters varied	(Ramos-Escudero et al., 2022)
27	Plant Phenotyping	Image-based phenotyping	R2 0.81-0.94	(de Carvalho et al., 2022)
28	Plant Phenotyping	RGB value	Highest yield 1.797 g/L	(Ma et al., 2022)
29	Chemical Sensing	Smartphone DIC	R2 > 0.9965	(Caleb & Alshana, 2021)
30	Chemical Sensing	DIA (CIELAB a*)	R2 = 0.9754 vs pH meter	(Sri Sruthi et al., 2021)
31	Plant Phenotyping	DIA-PP	Inhibition 65-95%	(Sasamoto et al., 2021)
32	Chemical Sensing	RGB image analysis	Clear titration endpoint	(Caraballo et al., 2021)

33	Chemical Sensing	Digital imaging spot test	-	(de Oliveira et al., 2020)
34	Plant Phenotyping	DIA (scanning flour analyzer)	Consistent with colorimeter	(Steinberg et al., 2020)
35	Plant Phenotyping	DIA	Correlated with carotenoid content	(Salazar-González et al., 2020)
36	Chemical Sensing	DIC	R2 > 0.99, LOD 0.04 mg/L	(Choodum et al., 2020)
37	Chemical Sensing	Smart device DIC	Equivalent to UV-Vis & HPLC	(Wongthanyakram et al., 2019)
38	Textile	Scanner (RGB→CIELab)	Comparable to spectrophotometer	(Nateri et al., 2019)
39	Plant Phenotyping	DIA tool (Color Test)	-	(Lozano-Cavazos et al., 2018)
40	Plant Phenotyping	DIA	Kernel variation up to 19.67%	(Tańska, Ambrosewicz-Walacik, et al., 2018)
41	Plant Phenotyping	DIA (RGB/HSI/Lab)	Correlated with chlorophyll-color	(Tańska, Buczek, et al., 2018)
42	Plant Phenotyping	Digital photography+ RGB	More accurate than reflectance	(del Valle et al., 2018)
43	Plant Phenotyping	DIA (L*a*b*C*)	Significant change observed	(Afsharnia et al., 2017)
44	Plant Phenotyping	DIA(RGB)+hyperspectral	R2 up to 0.91	(Elsayed et al., 2016)

*Note: CIELAB = CIE L*a*b* color space; CNN = convolutional neural network; DIA = digital image analysis; DIA-PP = digital image analysis with protoplast co-culture method; DIC = digital image colorimetry; FAAS = flame atomic absorption spectrometry; GC-FID = gas chromatography with flame ionization detection; HPLC = high-performance liquid chromatography; HSB = hue, saturation, brightness; HSI = hue, saturation, intensity; LOD = limit of detection; ML = machine learning; MSE = mean squared error; PSNR = peak signal-to-noise ratio; RGB = red, green, blue; TVB-N = total volatile basic nitrogen; UV-Vis = ultraviolet-visible spectrophotometry.*

Analysis of the publication year distribution (Figure 4) shows a consistent upward trend in DIC-related research on natural dyes and pigments, rising from a single publication in 2016 to a peak of eight publications in 2022, and remaining high through 2025-2026. This pattern indicates that interest in DIC as a natural-pigment measurement method has intensified substantially over the past decade, consistent with the broader trend toward accessible, low-cost analytical technologies described in the Introduction.

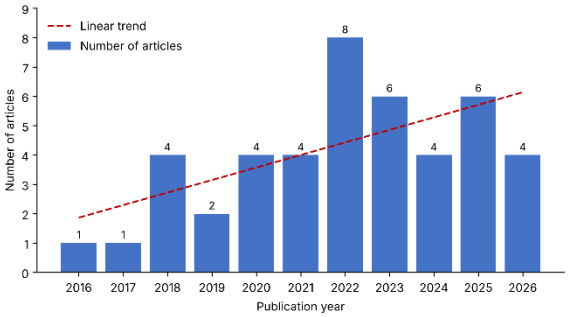


Figure 4. Publication year distribution (n = 44).

To answer the primary research question of this review, the distribution of DIC applications across domains was quantified (Figure 5). The results show that DIC applications are concentrated in chemical sensing (45%, 20 articles) and plant phenotyping (39%, 17 articles), while food packaging accounts for 11% (5 articles) and textile dyeing accounts for only 4.5% (2 articles) of the total corpus.

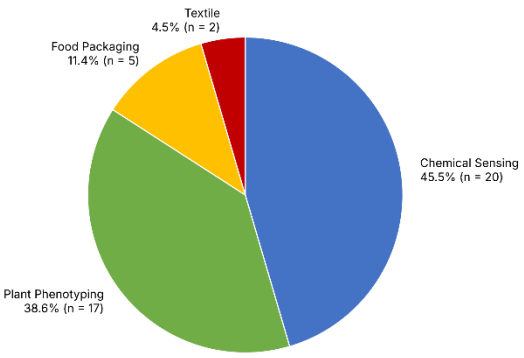


Figure 5. Distribution of DIC application domains (n = 44). Percentages may not sum to 100% due to rounding.

Validity of DIC Relative to Conventional Methods

The validity of DIC as a color quantification method is grounded in the principle that the intensity of red, green, and blue channels captured in a digital image, or their transformation into CIELAB coordinates, varies systematically and predictably with the concentration of a colored analyte or pigment, in a manner analogous to the relationship between absorbance and concentration described by the Beer-Lambert law in conventional spectrophotometry. If this theoretical relationship holds, DIC-derived color values should correlate strongly with results obtained through conventional instruments across diverse sample types.

This expectation is supported by the evidence synthesized in this review, with differences between domains. Among the 11 chemical sensing studies that reported a correlation coefficient (R^2 or r) against a conventional method, 9 reported values above 0.99 (Table 1), and in several cases no statistically significant difference was found between the two methods (Choodum et al., 2020; Phatthanawiwat et al., 2022). Plant phenotyping studies, in which color is related to pigment content in heterogeneous biological material, reported lower and more variable values, with R^2 ranging from 0.57 to 0.94 (Agarwal et al., 2025; de Carvalho et al., 2022). Agreement with a reference instrument was also reported for scanner-based color measurement of madder-dyed nylon (Nateri et al., 2019). Overall, the evidence indicates that the theoretical basis of DIC holds across heterogeneous pigments, devices, and applications, with the strongest agreement in chemical sensing.

Linearity and Contradiction with Previous Research

The findings of this review are largely linear with, and extend, observations made in individual primary studies. Prior authors working within specific domains, such as Zhang et al. (2026) in food packaging and Suchowilska et al. (2022) in plant phenotyping, have each independently noted the accessibility and validity advantages of DIC within their respective fields. However, none of these individual studies were positioned to assess how evenly this evidence is distributed across domains as a whole. The present review does not contradict these individual findings; rather, it provides the first quantitative account of the imbalance that emerges when they are viewed collectively; an imbalance that could not be observed from any single primary study in isolation.

With respect to the textile domain specifically, the two available studies show a degree of contradiction in their reported strength of evidence. Nateri et al. (2019) reported that scanner-based DIC produced results comparable to spectrophotometric measurement for madder-dyed nylon fabric, suggesting high method agreement consistent with findings in other domains. In contrast, Batarius et al., (2022) reported measurable color degradation using MSE and PSNR parameters without a direct spectrophotometric comparison, meaning the quantitative validity of DIC in that specific study was not established against a reference method. This distinction is an important nuance: while DIC has been shown to be technically applicable to textile evaluation, only one of the two available studies has actually validated it against a conventional method, indicating that the evidentiary basis for textile applications is not only smaller in

volume but also less methodologically consistent than in the three dominant domains.

The small number of textile studies may reflect how DIC has been used in this field. Nateri et al. (2019) positioned DIC as a substitute for the spectrophotometer, converting scanner-derived RGB values to CIELAB and comparing them with reference measurements on madder-dyed nylon, so agreement between methods was the outcome of interest. Batarius et al., (2022), in contrast, used the image-quality metrics MSE and PSNR to track the degradation of naturally dyed woven fabric under sunlight, so DIC served to monitor change within one material rather than to be benchmarked against a reference instrument. The two studies therefore differ in objective, color metric, and validation strategy, which prevents direct comparison and leaves no common protocol for textile applications. In the other three domains, color values are typically calibrated against analyte concentration or pigment content and compared with a reference method (Table 1). Standardizing image capture conditions and color metrics, and validating them against spectrophotometric measurement, is therefore the main methodological need identified by this review for natural dye-based textile evaluation. Because the search terms combined DIC-related and natural pigment terms (see Limitations), textile studies that use other terminology may not have been captured.

Implications for Chemistry Education

The concentration of DIC research in analytical and agricultural contexts, rather than education-oriented applications, also points to an underexplored opportunity within chemistry education. Ritonga and Nurfajriani. (2026) demonstrated the feasibility of augmented reality-based Android applications for abstract chemistry concepts, while Nafillah et al. (2026) demonstrated that freely accessible simulation tools can effectively substitute for limited laboratory facilities in practical chemistry instruction, and Sianturi et al. (2026) similarly integrated PhET simulation into a discovery learning-based e-module for reaction rate material. Likewise, Wardani et al. (2022) developed a laboratory module on the UV-Visible spectra of natural compounds used as dye sensitizers and reported it to be valid, practical, and effective for chemistry education students, showing that practicum modules built around natural dyes can be packaged as teaching material. However, the successful classroom adoption of such tools depends not only on their technical validity but also on teacher readiness. Sabrina & Suprihatiningrum, (2026) found that digital pedagogical competence among pre-service chemistry teachers remains uneven, suggesting that any future integration of DIC into chemistry education would similarly require attention to teacher preparedness, not solely technical validation. Furthermore, the smartphone-based and low-cost nature of DIC aligns closely with the participatory, accessible ethos of citizen science approaches in chemistry education, as illustrated by Abdjul et al. (2026), whose citizen science-based thermochemistry module was designed to strengthen scientific literacy through direct student engagement with real-world phenomena using accessible tools. It remains to be tested empirically whether DIC can serve as an entry point for participatory, inquiry-based learning grounded in local wisdom-based natural dye practices; no study in the current literature has examined this application.

Limitations

Several limitations should be considered. First, only the Scopus database was searched, so relevant studies indexed elsewhere were not captured. Second, because of limited institutional access, full-text screening could not be completed for all records, and screening relied mainly on titles and abstracts. Third, domain classification and thematic clustering were performed by a single reviewer with AI assistance, without inter-rater verification, which may introduce classification bias. Fourth, the search covered English-language journal articles published between 2016 and 2026, thereby excluding

earlier foundational work and studies in other languages. Finally, validity outcomes were recorded as reported in the primary studies without re-analysis, and no formal risk-of-bias assessment was conducted; the synthesis of validity is therefore descriptive.

CONCLUSION

This review mapped 44 articles on the application of Digital Image Colorimetry (DIC) to natural dyes and pigments published between 2016 and 2026. In response to the first research question, DIC applications are concentrated in chemical sensing (45%) and plant phenotyping (39%), followed by food packaging (11%), with textile dyeing represented by only two studies (4.5%). In response to the second, DIC showed high agreement with conventional methods: 9 of 11 chemical sensing studies reporting correlation coefficients exceeded 0.99, whereas plant phenotyping studies reported lower and more variable values (R^2 0.57 to 0.94). In response to the third, the main gap lies in textile dyeing, where only one of the two studies validated DIC against a spectrophotometer. Future studies should therefore standardize image capture conditions and color metrics for textile color evaluation and validate them against spectrophotometric measurement. As a low-cost, smartphone-based tool, DIC has also not yet been examined in chemistry education, and its use in natural dye-based practicum activities can be tested in future research.

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REFERENCE

Abdjul, R., Lukum, A., & Botutihe, D. N. (2026). Development of a Citizen Science-Based Thermochemistry Module Oriented toward Scientific Literacy and Environmental Awareness. *Jurnal Inovasi Pembelajaran Kimia (Journal of Innovation in Chemistry Education)*, *8*(1), 1–10. https://doi.org/10.24114/ygyn7d19

Afsharnia, F., Mehdizadeh, S. A., Ghaseminejad, M., & Heidari, M. (2017). The effect of dynamic loading on abrasion of mulberry fruit using digital image analysis. *Information Processing in Agriculture*, *4*(4), 291–299. https://doi.org/10.1016/j.inpa.2017.07.003

Agarwal, A., De Jesus Colwell, F., Correa Galvis, V. A., Hill, T. R., Boonham, N., & Prashar, A. (2025). Assessing nutritional pigment content of green and red leafy vegetables by image analysis: Catching the “red herring” of plant digital color processing via machine learning. *Biology Methods and Protocols*, *10*(1). https://doi.org/10.1093/biomethods/bpaf027

Alikord, M., Shariatifar, N., Saraji, M., Hosseini, H., Khaniki, G. J., Shoeibi, S., Rezazadeh, T., & Fazeli, M. (2025). Bio-nanoparticles sensor couple with smartphone digital image colorimetry and dispersive liquid–liquid microextraction for aflatoxin B1 detection. *Scientific Reports*, *15*(1). https://doi.org/10.1038/s41598-025-92944-3

Bao, Y., Wang, M., Li, J., Yang, X., Wen, B., Wang, L., He, Y., Si, X., & Li, B. (2024). A starch-based 3D printed intelligent colorimetric film co-loaded natural pigments for visualizing food freshness: Effect of nozzle size on gel structure formation. *Food Hydrocolloids*, *155*. https://doi.org/10.1016/j.foodhyd.2024.110218

Batarius, P., Sinlae, A. A., & Fahik, E. F. (2022). Analysis of the Quality of Natural Dyes in Weaving Exposed to

Sunlight Using MSE and PSNR Parameters. *Jurnal RESTI*, *6*(5), 797–802. https://doi.org/10.29207/resti.v6i5.4339

Caleb, J., & Alshana, U. (2021). Supramolecular solvent-liquid-liquid microextraction followed by smartphone digital image colorimetry for the determination of curcumin in food samples. *Sustainable Chemistry and Pharmacy*, *21*. https://doi.org/10.1016/j.scp.2021.100424

Caleb, J., Alshana, U., Ertaş, N., & Bakırdere, S. (2023). Smartphone digital image colorimetry combined with dispersive solid-phase microextraction for the determination of boron in food samples. *Food Chemistry*, *426*. https://doi.org/10.1016/j.foodchem.2023.136528

Caleja-Ballesteros, H. J. R., & Ballesteros, J. I. (2023). Digital image-based quantification of ethanol in distilled spirits using red cabbage (Brassica oleracea) extract. *Chemical Papers*, *77*(12), 7977–7984. https://doi.org/10.1007/s11696-023-03034-5

Caraballo, R. M., Saleh Medina, L. M., Gomez, S. G. J., Vensaus, P., & Hamer, M. (2021). Turmeric and RGB Analysis: A Low-Cost Experiment for Teaching Acid-Base Equilibria at Home. *Journal of Chemical Education*, *98*(3), 958–965. https://doi.org/10.1021/acs.jchemed.0c01165

Chinnawat, S., Detsri, E., Lerdpiriyaskulkij, N., Teerasong, S., & Mathaweesansurn, A. (2025). Smartphone RGB camera-based colorimetric platform with double-layer spherical Ca(II)-alginate/ZnONPs hydrogel liquid-core curcumin emulsion for rapid and selective detection of pyridoxine (Vitamin B6) in functional beverages. *Microchemical Journal*, *215*. https://doi.org/10.1016/j.microc.2025.114204

Choodum, A., Jirapattanasophon, V., Boonkanon, C., Taweekarn, T., & Wongniramaikul, W. (2020). Difluoroboron-curcumin doped starch film and digital image colorimetry for semi-quantitative analysis of arsenic. *Analytical Sciences*, *36*(5), 577–582. https://doi.org/10.2116/ANALSCI.19SBP09

Claudio Martins, L., Soares, S., & Rocha, F. R. P. (2023). Digital-image eco-friendly spot test with liquid–liquid microextraction for selective determination of flavonols in berries. *Microchemical Journal*, *193*. https://doi.org/10.1016/j.microc.2023.109207

de Carvalho, R. R. B., Cortes, D. F. M., e Sousa, M. B., de Oliveira, L. A., & de Oliveira, E. J. (2022). Image-based phenotyping of cassava roots for diversity studies and carotenoids prediction. *PLoS ONE*, *17*(1). https://doi.org/10.1371/journal.pone.0263326

de Oliveira, L. M. A., dos Santos, V. B., da Silva, E. K. N., Lopes, A. S., & Dantas-Filho, H. A. (2020). An environment-friendly spot test method with digital imaging for the micro-titration of citric fruits. *Talanta*, *206*. https://doi.org/10.1016/j.talanta.2019.120219

del Valle, J. C., Gallardo-López, A., Buide, M. L., Whittall, J. B., & Narbona, E. (2018). Digital photography provides a fast, reliable, and noninvasive method to estimate anthocyanin pigment concentration in reproductive and vegetative plant tissues. *Ecology and Evolution*, *8*(6), 3064–3076. https://doi.org/10.1002/ece3.3804

Dong, S., Zhang, Y., Lu, D., Gao, W., Zhao, Q., & Shi, X. (2023). Multifunctional intelligent film integrated with purple sweet potato anthocyanin and quercetin-loaded chitosan nanoparticles for monitoring and maintaining freshness of

shrimp. *Food Packaging and Shelf Life*, *35*. https://doi.org/10.1016/j.fpsl.2022.101022

Elsayed, S., Galal, H., Allam, A., & Schmidhalter, U. (2016). Passive reflectance sensing and digital image analysis for assessing quality parameters of mango fruits. *Scientia Horticulturae*, *212*, 136–147. https://doi.org/10.1016/j.scienta.2016.09.046

Eskandari, A., Namdari, R., & Seidi, S. (2024). Hyphenated Centrifugal Microsolid Phase Extraction and Centrifugal Acceleration Thin-Layer Chromatography in a Single Device: An Innovative Approach to Perform Consecutive Extraction and Separation. *Analytical Chemistry*, *96*(49), 19537–19544. https://doi.org/10.1021/acs.analchem.4c04252

Ismail, S., Abdullahi, A. B., & Alshana, U. (2024). Edible oil-based switchable-hydrophilicity solvent liquid-liquid microextraction prior to smartphone digital image colorimetry for the determination of total curcuminoids in food samples. *Analytical Methods*, *16*(24), 3983–3992. https://doi.org/10.1039/d4ay00250d

Jantra, J., Teepoo, S., & Thananimit, S. (2024). Smartphone-based imaging colorimetric assay for monitoring the quality of curcumin in turmeric powder. *Analytical Sciences*, *40*(7), 1311–1321. https://doi.org/10.1007/s44211-024-00562-2

Komyshev, E. G., Genaev, M. A., Busov, I. D., Kozhekin, M. V, Artemenko, N. V, Glagoleva, A. Y., Koval, V. S., & Afonnikov, D. A. (2023). Determination of the melanin and anthocyanin content in barley grains by digital image analysis using machine learning methods; [Определение содержания меланина и антоцианов в зернах ячменя на основе анализа цифровых изображений методами машинного обучения]. *Vavilovskii Zhurnal Genetiki i Selektsii*, *27*(7), 859–868. https://doi.org/10.18699/VJGB-23-99

Li, S., Jiang, Y., Zhou, Y., Li, R., Jiang, Y., Alomgir Hossen, M., Dai, J., Qin, W., & Liu, Y. (2022). Facile fabrication of sandwich-like anthocyanin/chitosan/lemongrass essential oil films via 3D printing for intelligent evaluation of pork freshness. *Food Chemistry*, *370*. https://doi.org/10.1016/j.foodchem.2021.131082

Lorenzo, N. D., da Rocha, R. A., Papaioannou, E., Tessaro, L. L. G., & Nunes, C. A. (2025). Rapid estimation of natural pigments in olive and avocado oils using a colorimetric sensor. *Journal of Food Composition and Analysis*, *145*. https://doi.org/10.1016/j.jfca.2025.107773

Lozano-Cavazos, C. J., Valdez-Aguilar, L. A., Ibarra-Jiménez, L., Ascacio-Valdés, J. A., Benavides-Mendoza, A., Aguilar-González, C. N., & Guajardo-Ríos, O. (2018). Animal-based organic nutrition induces comparable fruit quality to that of inorganic fertigation in soilless-grown grape tomato. *Acta Agriculturae Scandinavica Section B: Soil and Plant Science*, *68*(6), 515–523. https://doi.org/10.1080/09064710.2018.1437215

Ma, Z., Liu, X., Liu, Y., Chen, W., & Wang, C. (2022). Studies on the biosynthetic pathways of melanin in Auricularia auricula. *Journal of Basic Microbiology*, *62*(7), 843–856. https://doi.org/10.1002/jobm.202100670

Matthew, S. A. L., Egan, G., Witte, K., Kaewchuchuen, J., Phuagkhaopong, S., Totten, J. D., & Seib, F. P. (2022). Smart Silk Origami as Eco-sensors for Environmental Pollution. *ACS Applied Bio Materials*, *5*(8), 3658–3666. https://doi.org/10.1021/acsabm.2c00023

Nafillah, K., Ariyani, H. D., Nindita, K., Kurniawan, F. S., & Aufi, A. U. (2026). Effectiveness of PhET Simulation in Acid-Base Practicum for Maritime Engineering Students: Alignment with IMO Model Course 7.04. *Jurnal Inovasi Pembelajaran Kimia (Journal of Innovation in Chemistry Education)*, *8*(1), 24–34. https://doi.org/10.24114/16jkaq62

Nandini, Angel, Kumar, S., & Jose, D. A. (2026). From spice to sensor: Curcumin as a natural colorimetric sensor for H2O and D2O and its applications using electrospun nanofibers and smartphone. *Microchemical Journal*, *226*. https://doi.org/10.1016/j.microc.2026.118513

Nateri, A. S., Hajipour, A., & Dehnavi, E. (2019). Colorimetric study of absorption behavior of madder natural dye on nylon using scanner. *Indian Journal of Fibre and Textile Research*, *44*(3), 352–357.

Page, M. J., McKenzie, J. E., & Bossuyt, P. M. (2021). The PRISMA 2020 statement: an updated guideline for reporting systematic reviews. *BMJ*, *372*, n71. https://doi.org/10.1136/bmj.n71

Phatthanawiwat, K., Boonkanon, C., Wongniramaikul, W., & Choodum, A. (2022). Catechin and curcumin nanoparticle-immobilized starch cryogels as green colorimetric sensors for on-site detection of iron. *Sustainable Chemistry and Pharmacy*, *29*. https://doi.org/10.1016/j.scp.2022.100782

Ramos-Escudero, F., Gómez-Coca, R. B., Muñoz, A. M., Fuente-Carmelino, L. D. L., & Pérez-Camino, M. D. C. (2022). Oil From Three Aguaje Morphotypes (Mauritia flexuosa L.f.) Extracted by Supercritical Fluid With CO2: Chemical Composition and Chromatic Properties. *Frontiers in Sustainable Food Systems*, *6*. https://doi.org/10.3389/fsufs.2022.843772

Ritonga, D. A., & Nurfajriani. (2026). Development of Augmented Reality-Based Android Applications on Chemical Bonding Material. *Jurnal Inovasi Pembelajaran Kimia (Journal of Innovation in Chemistry Education)*, *8*(1), 50–62. https://doi.org/10.24114/j5hbta24

Sabrina, S. A., & Suprihatiningrum, J. (2026). Self-Assessment on Digital Pedagogy of Indonesian Gen Z Student-Teachers. *Jurnal Inovasi Pembelajaran Kimia (Journal of Innovation in Chemistry Education)*, *8*(1), 11–23. https://doi.org/10.24114/qcdqz713

Salazar-González, C. Y., Rodríguez-Pulido, F. J., Stinco, C. M., Terrab, A., Díaz-Moreno, C., Fuenmayor, C., & Heredia, F. J. (2020). Carotenoid profile determination of bee pollen by advanced digital image analysis. *Computers and Electronics in Agriculture*, *175*. https://doi.org/10.1016/j.compag.2020.105601

Sasamoto, H., Suzuki, S., Mardani-Korrani, H., Sasamoto, Y., & Fujii, Y. (2021). Allelopathic activities of three carotenoids, neoxanthin, crocin and β-carotene, assayed using protoplast co-culture method with digital image analysis. *Plant Biotechnology*, *38*(1), 101–107. https://doi.org/10.5511/plantbiotechnology.20.1211a

Shabrina, A. N., Nursa'adah, E., & Firdaus, M. L. (2025). Quantitative Detection of Hexavalent Chromium in Aquatic Environments Using Digital Image Colorimetry and the Green Chemistry Approach. *ACS Sustainable Chemistry and Engineering*, *13*(24), 9177–9185. https://doi.org/10.1021/acssuschemeng.5c02305

Sianturi, Y. A., Purba, J., & Panggabean, F. T. M. (2026). Development of Discovery Learning E-Module Integrated with PhET Simulation on Reaction Rate Material. *Jurnal Inovasi Pembelajaran*

Kimia (Journal of Innovation in Chemistry Education), *8*(1), 88–98. https://doi.org/10.24114/vv4n6862

Sonawane, A. D., Bansal, H., & Mahajan, P. V. (2026). Curcumin-based colourimetric CO2 indicators for low-range headspace screening. *Applied Food Research*, *6*(2). https://doi.org/10.1016/j.afres.2026.102508

Sri Sruthi, P., Balasubramanian, S., Senthil Kumar, P., Kapoor, A., Ponnuchamy, M., Mariam Jacob, M., & Prabhakar, S. (2021). Eco-friendly pH detecting paper-based analytical device: Towards process intensification. *Analytica Chimica Acta*, *1182*. https://doi.org/10.1016/j.aca.2021.338953

Steinberg, T. S., Meleshkina, E. P., Shvedova, O. G., Morozova, O. V, & Zhiltsova, N. S. (2020). Changes of the Optical Properties of Top-Grade Flour (Semolina) from Durum Wheat During Its Ripening. *Pisevye Sistemy/Food Systems*, *3*(2), 24–28. https://doi.org/10.21323/2618-9771-2020-3-2-24-28

Suchowilska, E., Wiwart, M., Wachowska, U., Radawiec, W., Combrzyński, M., & Gontarz, D. (2022). A comparison of phenotypic variation in Triticum durum Desf. genotypes deposited in gene banks based on the shape and color descriptors of kernels in a digital image analysis. *PLoS ONE*, *17*(2 February). https://doi.org/10.1371/journal.pone.0259413

Tańska, M., Ambrosewicz-Walacik, M., Jankowski, K., & Rotkiewicz, D. (2018). Possibility use of digital image analysis for the estimation of the rapeseed maturity stage. *International Journal of Food Properties*, *20*, S2379–S2394. https://doi.org/10.1080/10942912.2017.1371188

Tańska, M., Buczek, J., Jarecki, W., Wasilewska, A., & Konopka, I. (2018). Grain morphology, texture and colour-related compounds of bread wheat cultivars in relation to cultivation regimes and growing location; [Paprastųjų kviečių grūdų morfologinių savybių, tekstūros ir spalvos priklausomumas nuo auginimo aplinkos ir vietos]. *Zemdirbyste*, *105*(2), 105–112. https://doi.org/10.13080/z-a.2018.105.014

Wardani, N. K. M. S., Siahaan, J., Rahmawati, R., & Hadisaputra, S. (2022). UV-Visible Spectra Analysis of Natural Compounds Sensitized by Dyes: Development of a Computational Chemistry Laboratory Module. *Jurnal Inovasi Pembelajaran Kimia (Journal of Innovation in Chemistry Education)*, *4*(1), 66–73. https://doi.org/10.24114/jipk.v4i1.33640

Wirojsaengthong, S., Aeungmaitrepirom, W., Unob, F., Fuangswasdi, S., Varanusupakul, P., Mueangdech, K., Treetos, T., & Puthongkham, P. (2023). Portable Quantitative Chemical Analysis: Digital Image Colorimetric Detection of Fe(III) with Curcumin Paper. *Journal of Chemical Education*, *100*(9), 3604–3611. https://doi.org/10.1021/acs.jchemed.3c00483

Wongthanyakram, J., Harfield, A., & Masawat, P. (2019). A smart device-based digital image colorimetry for immediate and simultaneous determination of curcumin in turmeric. *Computers and Electronics in Agriculture*, *166*. https://doi.org/10.1016/j.compag.2019.104981

Zantioti, C., & Malandrakis, E. E. (2026). Effects of Lyophilized Dietary Yeast Rhodotorula mucilaginosa on Skin and Fillet Pigmentation of Gilthead Seabream (Sparus aurata): A Computer-Based Image Analysis Assessment. *Aquaculture Journal*, *6*(1). https://doi.org/10.3390/aquacj6010010

Zhang, Y., Peng, D., He, X., Zheng, H., Xiao, J., Xu, D., & Yang, N. (2026). Blueberry anthocyanins-functionalized hydrogel labels for smartphone-assisted real-time visual freshness monitoring of perishable proteins. *Talanta*, *297*. https://doi.org/10.1016/j.talanta.2025.128813

Zykin, P. A., Andreeva, E. A., Tsvetkova, N. V, Bulanov, A. N., & Voylokov, A. V. (2025). Anatomical and Digital Image Analysis of Flavonoid-Mediated Grain Coloration in Rye (Secale cereale L. *). Plants*, *14*(16). https://doi.org/10.3390/plants14162557