



Potential of Anthocyanins as Natural Colorants for Printing Inks: A Review

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ABSTRACT

Anthocyanins are natural pigments belonging to the flavonoid group that exhibit red, purple, and blue colors and have potential as natural colorants for printing inks. The development of bio-based colorants is one approach to supporting the use of more sustainable materials in printing technology. This article reviews the potential of anthocyanins as natural colorants for printing inks based on their chemical characteristics, color properties, stability, and factors affecting their application in printing systems. A structured literature review was conducted with priority given to publications from 2020-2026 related to anthocyanins, color stability, inks, printing processes, and ink substrate interactions. The review indicates that molecular structure and environmental conditions strongly determine anthocyanin color characteristics. Changes in pH, temperature, light exposure, and oxygen can induce structural transformations and degradation that affect color stability. Experimental evidence shows that anthocyanin rich extracts have been formulated into inks for screen printing, indicator inks, and functional printing systems. Interactions with ink formulations and substrates, including materials containing calcium carbonate, may also alter printed color. Strategies such as pH control, selection of more stable anthocyanins, and copigmentation may improve performance. Anthocyanins therefore show promise as natural printing ink colorants, although formulation optimization and print color durability assessment are still required before broader application.

Keyword: Anthocyanins, Natural Colorants, Printing Ink, Color Stability, Sustainable Printing

ABSTRAK

Antosianin merupakan pigmen alami dari kelompok flavonoid yang memiliki karakteristik warna merah, ungu, hingga biru dan berpotensi dikembangkan sebagai bahan pewarna alami pada tinta cetak. Pengembangan bahan pewarna berbasis sumber hayati menjadi salah satu pendekatan untuk mendukung penggunaan material yang lebih berkelanjutan pada teknologi pencetakan. Artikel ini bertujuan mengkaji potensi antosianin sebagai pewarna alami pada tinta cetak berdasarkan karakteristik kimia, sifat warna, stabilitas, serta faktor yang memengaruhi penerapannya pada sistem pencetakan. Metode yang digunakan adalah tinjauan literatur terstruktur dengan prioritas publikasi 2020-2026 yang relevan dengan antosianin, stabilitas warna, tinta, proses pencetakan, dan interaksi tinta-substrat. Hasil kajian menunjukkan bahwa struktur kimia dan kondisi lingkungan sangat menentukan karakteristik warna antosianin. Perubahan pH, suhu, paparan cahaya, dan oksigen dapat menyebabkan perubahan struktur serta degradasi yang berdampak pada kestabilan warna. Bukti eksperimental menunjukkan ekstrak kaya antosianin telah diformulasikan menjadi tinta untuk screen printing, tinta indikator, dan sistem pencetakan fungsional. Interaksi dengan formulasi dan substrat, termasuk material yang mengandung kalsium karbonat, dapat memengaruhi warna hasil cetak. Strategi seperti pengendalian pH, pemilihan antosianin yang lebih stabil, dan kopigmentasi berpotensi meningkatkan kinerjanya. Antosianin memiliki prospek sebagai pewarna alami pada tinta cetak, tetapi optimasi formulasi dan evaluasi ketahanan warna masih diperlukan sebelum penerapan yang lebih luas.

Kata Kunci: Antosianin, Pewarna Alami, Tinta Cetak, Stabilitas Warna, Pencetakan Berkelanjutan



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1. Introduction

The printing industry continues to expand with increasing demand for printed products, packaging, labels, and visual communication media. Printing inks generally contain a colorant, binder, solvent or vehicle, and functional additives. Plant derived colorants and bio based or edible inks have been investigated for markers, screen printing, packaging, and other applications, although practical implementation remains constrained by rheology, runnability, color definition, color fastness, and stability [1,10,11,24].

Anthocyanins are water soluble flavonoid pigments widely distributed in fruits, vegetables, flowers, and other plant tissues [2,3,12]. Chemically, anthocyanins are glycosylated derivatives of anthocyanidins. The most common anthocyanidin aglycones include pelargonidin, cyanidin, delphinidin, peonidin, petunidin, and malvidin [3,6,12]. Structural variation, including hydroxylation, methoxylation, glycosylation, and acylation, contributes to differences in color and stability.

Anthocyanin color is closely related to molecular structure and environmental conditions. Changes in pH alter the equilibrium among the flavylium cation, quinonoidal base, hemiketal, and chalcone forms, producing visible color changes [2,5,12,13]. Temperature, light, oxygen, moisture, polymer interactions, and storage conditions further affect stability and color retention [2,5,13,17].

Stability is particularly important when anthocyanins are considered for printing inks. Dimic Misic et al. [1] demonstrated that anthocyanin rich plant dye inks can interact with modern calcium carbonate (CaCO₃) containing substrates, and that substrate chemistry and optical properties can influence printed appearance and color gamut [1]. Direct experimental evidence also shows that anthocyanin rich materials can be incorporated into printable systems. Klancnik and Koradin [7] prepared nine printing formulations from staghorn sumac extract for screen printing; Aldawsari et al. [10] used screen printing to prepare anthocyanin based authentication films; Hu et al. [8] developed a pH responsive anthocyanin containing ink for screen printing on coated paper; Tan et al. [9] investigated a 3D printed anthocyanin system; and Hong [31] evaluated screen printing of Aronia melanocarpa extract chitosan mixtures on cotton textiles.

Despite the extensive literature on anthocyanin chemistry, stabilization, and intelligent packaging [12–17,25], studies directly connecting anthocyanin chemistry with printing ink performance remain limited. Therefore, this review evaluates anthocyanins as natural printing colorants by integrating chemical structure, botanical source, analytical characterization, color and stability, formulation, printing evidence, substrate interactions, and remaining research needs.

2. Methods

This article uses a structured literature review approach to integrate evidence from anthocyanin chemistry, color stability, ink formulation, printing technology, and ink–substrate interactions. The objective is conceptual and comparative synthesis rather than meta analysis because formulation, substrate, printing process, and testing protocols vary substantially among studies.

The literature-search framework used in preparing this review covered scientific publications available through September 2026. Searches were designed around PubMed, Scopus, ScienceDirect, and Google Scholar, supplemented by backward and forward citation searching of key articles. Records were screened for topical relevance and then assessed against the inclusion and exclusion criteria. Search terms included “anthocyanin”, “anthocyanidin”, “anthocyanin-rich extract”, “purified anthocyanin”, “natural colorant”, “printing ink”, “anthocyanin ink”, “screen printing”, “inkjet printing”, “3D printing”, “4D printing”, “color stability”, “HPLC-DAD”, “LC-MS/MS”, and “NMR”. Terms were combined using Boolean AND/OR operators.

Inclusion criteria comprised: (1) research articles or scientific reviews addressing anthocyanin structure, botanical sources, characterization, color, or stability; (2) studies reporting analytical methods for anthocyanin identification or quantification; (3) studies on ink formulation or printable material systems; and (4) studies directly using anthocyanins or anthocyanin-rich extracts in screen printing, inkjet printing, 3D/4D printing, or functional printing. Studies focused only on pharmacological or health effects without a connection to color, materials, stability, or printing were excluded. Review articles were used primarily for contextual or mechanistic evidence, whereas claims about printing performance were prioritized from primary research.

For each selected study, information was extracted on botanical source, colorant type (crude extract, anthocyanin enriched extract, or purified compound), anthocyanin composition when available, extraction method, analytical characterization (UV–Vis, HPLC-DAD/PDA, LC-MS/MS, NMR), colorant concentration, binder or matrix, printing method, substrate, rheological parameters, CIELAB/ ΔE or spectral data, stability/fastness tests, and study limitations. Evidence was compared thematically and according to its proximity to actual printing.

The synthesis was organized into six themes: (1) botanical sources and anthocyanin diversity; (2) structure color stability relationships; (3) analytical characterization; (4) stability and stabilization strategies; (5) direct printing evidence and ink substrate interactions; and (6) research gaps. Evidence from films, coatings, or smart packaging was not treated as equivalent to evidence from printed inks; these studies were used as mechanistic evidence or as potential technology transfer opportunities.

An important traceability limitation should be stated explicitly. The initial manuscript search did not preserve the number of records at each screening stage. Therefore, retrospective counts have not been fabricated. The initial synthesis was based on 25 references, while the final submission should populate the identification, duplicate removal, screening, eligibility, and inclusion counts from the actual updated database search. Accordingly, the review is described as a structured review rather than a PRISMA-based systematic review (Table 1).

Table 1. Literature-search and synthesis framework.

Component	Search/synthesis strategy	Purpose
Publication period	Priority to 2020–2026; older studies retained when conceptually necessary	Capture recent developments while retaining essential foundations
Chemical focus	Structure, pH, temperature, light, oxygen, copigmentation, encapsulation	Explain color and stability mechanisms
Formulation focus	Binder, solvent/vehicle, humectant, thickener, viscosity/rheology	Connect pigment chemistry with printability
Printing focus	Screen printing, functional printing, 3D/4D printing, and relevant natural-ink studies	Assess evidence for printable systems
Performance focus	CIELAB/ ΔE , spectral response, fastness, drying, transfer, substrate effects	Assess print quality and durability
Synthesis	Thematic and comparative analysis	Identify patterns, trade-offs, and research gaps

3. Results and Discussion

3.1. Chemical Structure, Botanical Sources, and Color Properties

Anthocyanins are glycosylated derivatives of anthocyanidins, with cyanidin, delphinidin, pelargonidin, peonidin, petunidin, and malvidin representing the most common aglycones in plants [3,6,12]. Their chromatic behavior is not determined by concentration alone. Hydroxylation, methoxylation, glycosylation, and acylation alter the electronic environment of the flavylum chromophore and consequently affect hue, molar absorptivity, and resistance to degradation [3,4,12]. These structure property relationships are directly relevant to printing because the colorant must retain a predictable spectral response after incorporation into binders, humectants, thickeners, and other formulation components.

The six common anthocyanidins differ primarily in the substitution pattern of the B ring. Pelargonidin lacks hydroxyl groups at the 3' and 5' positions and generally favors red to orange-red hues. Cyanidin contains one additional hydroxyl group and commonly produces red to red-purple hues. Delphinidin has two B-ring hydroxyl groups and tends toward more bluish hues, but its higher hydroxylation can also increase susceptibility to oxidation. Peonidin is an O-methylated derivative of cyanidin and generally shows greater oxidative stability. Petunidin is partially methoxylated delphinidin, whereas malvidin contains two methoxy groups and is commonly associated with higher oxidative stability. In general, increased hydroxylation can

shift spectral response toward bluer hues but may increase oxidative reactivity, whereas methoxylation reduces oxidation sensitive hydroxyl sites and can improve stability.

Glycosylation also influences material behavior. Sugar residues, particularly at C3, increase water solubility and may provide steric protection to reactive sites, although glycosylation does not universally improve stability under all conditions. Acylation of sugar residues by aromatic acids such as p-coumaric, caffeic, or ferulic acid can promote intramolecular copigmentation and increase chromophore rigidity. Acylated anthocyanins can therefore show improved resistance to pH change, heat, and oxidation compared with non acylated analogues. In printing systems, however, structural changes also influence solubility, binder interactions, and ink transfer.

Botanical sources cannot be treated as chemically equivalent because their anthocyanin profiles differ. Blackberry and many berries are commonly rich in cyanidin-3-O-glucoside; blackcurrant contains substantial delphinidin derivatives; red grapes contain malvidin, delphinidin, petunidin, and peonidin derivatives; black rice is commonly rich in cyanidin-3-O-glucoside and peonidin-3-O-glucoside; purple corn contains cyanidin, pelargonidin, and peonidin-glycosides, including acylated derivatives; and purple sweet potato and red cabbage contain substantial acylated cyanidin based anthocyanins. In the *Aronia melanocarpa* printing study, cyanidin-3-galactoside was reported as the predominant anthocyanin, representing approximately 78% of total anthocyanins in the extract [31]. Thus, botanical source and molecular composition should be reported when comparing printing performance (Table 2).

Table 2. Representative botanical sources and anthocyanin composition relevant to printing.

Botanical source	Representative predominant anthocyanins	Material/printing relevance
<i>Aronia melanocarpa</i>	Cyanidin-3-galactoside (reported as predominant in the printing study)	Extract–chitosan screen printing on cotton [31]
Blackberry / berries	Often cyanidin-3-O-glucoside and related cyanidin derivatives	Potential source of red-purple colorants
Blackcurrant	Delphinidin glycosides and cyanidin derivatives	Higher hydroxylation; relevant to bluish color and stability
Red grape	Malvidin, delphinidin, petunidin, peonidin derivatives	Methoxylated anthocyanins; potentially greater oxidative stability
Black rice	Cyanidin-3-O-glucoside, peonidin-3-O-glucoside	Acylated and non-acylated pigment sources
Purple corn	Cyanidin-, pelargonidin-, and peonidin-glycosides; malonylated forms	Colorant source with structural diversity
Purple sweet potato	Acylated cyanidin derivatives	Strong pH-responsive color; relevant to indicators
Red cabbage	Acylated cyanidin derivatives	pH-responsive and functional-printing applications
Staghorn sumac	Anthocyanin-rich extract; complete molecular profile not established in all printing comparisons	Screen-printing dye source [7]

3.1.1. Analytical Characterization and Identification

Analytical characterization is essential because plant extracts are chemically complex mixtures. UV Vis spectroscopy is useful for spectral screening, monitoring chromophore changes, and estimating total anthocyanin content using pH differential approaches; however, UV Vis alone cannot reliably identify individual anthocyanins. HPLC-DAD/PDA is widely used to separate anthocyanins and support routine identification and quantification based on retention time and UV Vis spectra. LC-MS/MS provides molecular mass, precursor ion, and fragmentation information that can support annotation of anthocyanidin aglycones,

sugar residues, and acyl substituents. NMR, including ^1H , ^{13}C , HSQC, and HMBC experiments, provides more definitive structural information and is particularly valuable for complex or novel structures [26–30].

Because crude plant extracts contain anthocyanins together with other phenolics, organic acids, sugars, minerals, and matrix components, analytical characterization should distinguish among crude extracts, anthocyanin enriched extracts, and purified individual compounds. Crude extracts provide the most complex matrix; enriched extracts contain a higher anthocyanin fraction but remain mixtures; purified compounds permit more controlled structure property relationships. These materials should not be compared solely by plant name because non-anthocyanin components can modify pH, color, rheology, and stability (Table 3).

Table 3. Analytical approaches for anthocyanin characterization.

Method	Primary role	Main strength	Main limitation
UV–Vis	Spectral screening; total anthocyanin estimation	Rapid and relatively simple	Poor specificity for individual compounds
HPLC-DAD/PDA	Separation and routine quantification	Retention time + spectral information	Co-elution can complicate identification
LC-MS/MS	Molecular-mass and fragmentation evidence	Supports detailed compound annotation	Requires instrumentation and careful interpretation
NMR (^1H , ^{13}C , HSQC, HMBC)	Structural elucidation	Strong structural confirmation	Higher sample quantity and specialized analysis required

Anthocyanin color is strongly pH dependent. At low pH, the red flavylium cation predominates; with increasing pH, quinonoidal base, hemiketal, and chalcone forms become increasingly important [2,5,12,13]. The same extract can therefore display substantially different hues depending on its chemical environment. In printing, pH should be treated as a formulation variable rather than merely a storage parameter.

Copigmentation provides another level of control. Non-covalent association between anthocyanins and low molecular weight copigments can increase color intensity and modify spectral characteristics [4]. For printing, copigmentation may improve color strength and reduce instability, but the selected copigment must also be compatible with rheology, drying, and substrate interactions.

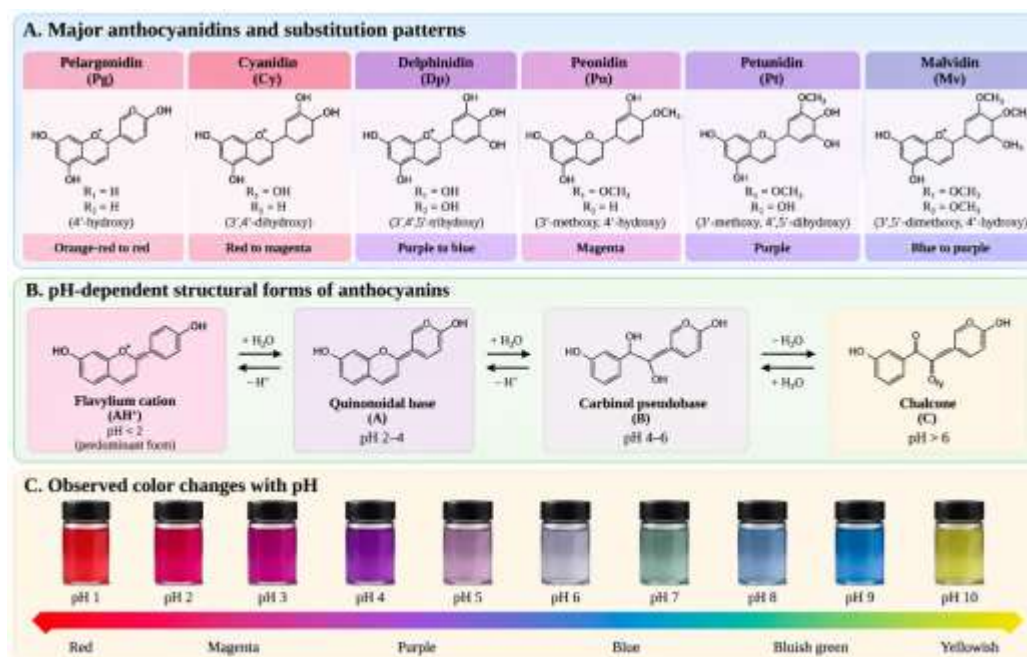


Figure 1. Simplified relationship between anthocyanidin substitution patterns, pH dependent anthocyanin forms, and observed color.

3.2. Anthocyanin Stability

Stability is a major limitation separating the attractive color properties of anthocyanins from broader use as printing colorants. pH, temperature, light, oxygen, moisture, molecular structure, and the surrounding matrix

are consistently identified as important degradation factors [2,5,17]. These factors are particularly relevant to printed products because the ink experiences storage, shear and exposure during printing, drying on the substrate, and subsequent exposure to light, heat, moisture, and air.

pH has a dual role: it controls visible hue through structural transformation and also affects chemical stability [2,5]. A pH that produces an attractive initial color may not provide the best long term stability. Consequently, a practical anthocyanin ink requires a defined operating pH range rather than adjustment based only on initial visual appearance.

Temperature and light create additional trade offs. Higher temperature accelerates degradation, while light can promote photochemical fading [2,5]. Nevertheless, Klancnik and Koradin [7] reported good to excellent light fastness for several staghorn sumac screen printed samples, including a value of 6 for many samples and 8 for a propanol-based-extract on fabric. This indicates that inherent anthocyanin sensitivity does not automatically translate into poor print fastness; extraction medium, ink matrix, substrate, and fixation mechanism can substantially influence final performance.

Oxygen and moisture also affect stability, particularly in responsive films and packaging systems [17]. Although such studies are not equivalent to conventional printing studies, their mechanisms remain relevant because printed anthocyanins become immobilized within a polymer matrix or substrate pores after drying. Encapsulation can protect anthocyanins from oxygen, light, heat, and unfavorable chemical conditions [15,16], but in printing systems it must also be evaluated for particle size, dispersion stability, mesh/nozzle compatibility, viscosity, and drying.

Table 4. Factors affecting anthocyanin stability and their implications for printing inks.

Factor	Effect on anthocyanins	Implication for printing inks
pH	Changes molecular form and color	Hue shift and reduced color consistency if uncontrolled
Temperature	Accelerates degradation	Reduced stability during processing/storage
Light	Promotes photodegradation	Reduced light fastness
Oxygen	Promotes oxidation	Color fading during storage/use
Moisture	Can accelerate degradation and matrix changes	Potential changes in color and adhesion
Copigmentation	May increase color intensity and stability	Potential stabilization, subject to formulation compatibility
Encapsulation	Can provide physical protection	May improve stability but can affect rheology/printability

3.3. Evidence for Anthocyanins as Printing Colorants

Direct printing studies provide the strongest application level evidence for evaluating anthocyanins as printing colorants. Klancnik and Koradin [7] extracted anthocyanin rich dye from staghorn sumac using solvents of different polarity and incorporated the extracts into pigment printing pastes. The study connected extraction chemistry with ink formulation, substrate, instrumental color measurement, and fastness. Solvent selection affected extract and print color, and only selected solvent systems produced uniform prints on paper and cotton. This demonstrates that extraction is inseparable from printing performance because the solvent influences both extraction efficiency and the chemical composition transferred into the ink.

The same study demonstrated the role of the ink vehicle. The plant extract was combined with an acrylic binder/thickener system, allowing a soluble plant dye to be used within a pigment printing framework. Very good rub fastness was obtained on the tested substrates, and cotton prints showed very good wet ironing fastness. Binder fixation can therefore compensate for some limitations of water soluble natural colorants.

Dimic Misic et al. [1] provided complementary evidence by examining anthocyanin rich plant dye inks on calcium carbonate containing substrates. Their results indicate that runnability, color definition, fastness, and functional stability depend on substrate chemistry and optical properties. Taken together with Klancnik and Koradin [7], the evidence supports a three way relationship: extraction/formulation determines the chemical

state of the anthocyanins, the binder controls immobilization and transfer, and the substrate influences the final optical and chemical environment.

Functional printing broadens the role of anthocyanins beyond conventional coloration. Aldawsari et al. [10] used screen printing to produce anthocyanin based authentication films with thermochromic and vapochromic responses, while Hu et al. [8] developed a pH responsive ink containing purple potato anthocyanin/curcumin and characterized viscosity, fluidity, smoothness, and initial drying before screen printing on coated paper. In these applications, pH sensitivity that may be undesirable for conventional color reproduction becomes a functional feature for sensors, authentication, and intelligent packaging.

Tan et al. [9] demonstrated shear thinning behavior in a 3D-printing system containing blueberry anthocyanins, with gallic acid used for copigmentation. The study reported reduced thermal fading while retaining printability related rheological behavior. The reported yield stress was 500–600 Pa. Chen et al. [22] demonstrated rapid pH-triggered color change in a 4D-printed pigment gel. Hong [31] further demonstrated screen printing of Aronia melanocarpa extract chitosan mixtures on cotton textiles. These studies illustrate different purposes and should not be interpreted as evidence for a single universal anthocyanin ink (Table 5).

Table 5. Comparative synthesis of printing-related studies relevant to anthocyanin ink development.

Study	Colorant/material type	Concentration/ratio	Binder or matrix	Printing method	Substrate	Quantitative/observed outcome
[1]	Anthocyanin-rich plant dye	Not directly comparable across formulations	Plant-dye ink system	DOD inkjet printing	CaCO ₃ -containing paper	Substrate chemistry affected color definition/gamut; inkjet dots were evaluated on paper
[7]	Staghorn sumac anthocyanin-rich extract	Aqueous system: 1.5 g extract/50 g printing paste	Acrylic binder/thickener	Screen printing	Paper and cotton	Selected formulations produced uniform prints; good excellent fastness reported
[8]	Purple potato anthocyanin/curcumin	Not reported in the comparative source	Carboxymethyl chitosan-based system	Screen printing	Coated paper	pH-responsive ink; viscosity, fluidity, smoothness and drying characterized
[9]	Blueberry anthocyanin + gallic acid	Not reported in the comparative source	Cassava starch ovalbumin system	3D printing	Intelligent label/gel system	Fade rate decreased from 35.13% to 26.44% at 90 °C; shear thinning behavior supported 3D printing
[10]	Red cabbage anthocyanin extract	Not reported	Film-forming matrix	Screen printing	Authentication film substrate	Thermochromic response (418→552)

						nm) and vapo-chromic response to ammonia (50–300 ppm)
[31]	Aronia melanocarpa extract chitosan	AE 0-40% (w/v) + 2% CS; 10% AE + 0-4% CS	Chitosan	Screen printing	Cotton textile	Cyanidin-3- galactoside ~78% of total anthocyanins; CS improved washing/light fastness; 40% AE gave ~70% antioxidant capacity
[11]	Mangosteen leaf plant dye (supporting natural ink evidence; not anthocyanin specific)	Formulation optimized by response surface	CMC + glycerol	Marker ink	Marker substrate	Formulation affected viscosity and color lightness

3.4. Challenges and Strategies for Performance Improvement

The main technological challenge is not simply that anthocyanins are unstable, but that the variables used to stabilize them also affect printability. pH adjustment changes color and chemical stability [2,5]; higher polymer or thickener levels may improve immobilization while increasing viscosity [8,11]; and encapsulation may protect the pigment but generate particles that affect dispersion or passage through printing elements [15,16]. These interactions indicate that optimization should be multi response rather than focused on a single property.

Rheology is particularly important. Mohd Basri et al. [11] quantitatively demonstrated that CMC concentration changes the viscosity of plant based marker ink, while Hu et al. [8] evaluated viscosity, fluidity, smoothness, and initial drying in a printable responsive ink. Tan et al. [9] showed that shear thinning behavior can be retained in a stabilized anthocyanin based 3D-printing system. Rheological targets must therefore be matched to the printing process. Screen printing can accommodate, and often requires, more structured pastes, whereas inkjet systems require much lower viscosity and tighter particle control.

Color measurement should extend beyond visual assessment. Klancnik and Koradin [7] used spectrophotometric evaluation to compare extracts, inks, and printed samples, while anthocyanin-film literature frequently uses total color difference to quantify response and stability [18-21]. Printing studies should combine CIELAB coordinates and ΔE with spectral reflectance, color strength, and relevant fastness tests. This distinction is necessary to separate formulations that merely produce attractive initial colors from those that retain reproducible color after printing and aging.

Substrate selection remains insufficiently developed. Differences between paper and cotton [7], together with CaCO₃ interactions [1], indicate that absorbency, surface chemistry, fillers, coating, and optical scattering can modify anthocyanin color. Substrate should therefore be treated as an experimental factor rather than a passive support. Future graphic arts studies should systematically compare uncoated paper, coated paper, recycled paper, and packaging board.

Four practical strategies emerge from the combined evidence: (1) define a specific operating pH range for each formulation; (2) optimize binder, humectant, and thickener levels for the target printing process; (3) apply copigmentation or encapsulation only after confirming that stabilization does not compromise printability; and

(4) adapt the formulation to substrate chemistry. This changes stability from a purely chemical problem into a formulation engineering problem aligned with printing requirements.

The conceptual framework is therefore structure → formulation → printing process → substrate → printed performance. Anthocyanin structure and stability determine the initial color state [2-5,12-17]; formulation controls viscosity, dispersion, and fixation [7-11]; the printing process controls transfer and layer formation; and substrate characteristics modify the final chemical and optical environment [1,7]. The output should be assessed using color and durability parameters. If ΔE , fastness, or printability does not meet the target, formulation, process conditions, or substrate selection must be adjusted.

The available evidence does not have equal strength. Studies [1] and [7-10,31] provide the most direct evidence for anthocyanin related printing, whereas studies [15-21,23,25] mainly provide mechanistic evidence from films or packaging matrices. Reference [11] provides supporting evidence for natural ink formulation optimization rather than anthocyanin specific printing. This distinction is important so that stabilization strategies demonstrated in non printing systems are not presented as fully validated conventional printing technologies.

Sustainability should also be interpreted cautiously. Replacing synthetic colorants with plant derived anthocyanins does not automatically make a printing system more sustainable. Extraction solvent, energy demand, binder chemistry, formulation stability, shelf life, waste generation, and reprinting caused by poor color consistency can all influence environmental performance. Because most reviewed studies do not provide life cycle assessments, terms such as “bio based”, “plant derived”, or “potentially more sustainable” are more appropriate unless environmental benefits have been demonstrated quantitatively.

3.5. Research Prospects

The literature shows an imbalance: anthocyanin chemistry and intelligent packaging have been extensively studied [12-21,25], whereas direct research on anthocyanins as printing-ink colorants remains comparatively limited [1,7-10,31]. Results obtained in solution or cast films cannot automatically be assumed to apply to printing because printing introduces shear, transfer, drying, penetration, binder fixation, and substrate dependent optical effects.

The first priority is to establish formulation process substrate relationships using experimental designs that vary anthocyanin concentration, pH, solvent system, binder, humectant, and rheology modifier while measuring both chemical stability and printing response. The response surface framework used for plant based marker ink [11] provides a useful methodological precedent because color and viscosity were treated as simultaneous responses.

The second priority is standardization of print quality assessment. Future studies should report CIELAB coordinates, ΔE after aging, spectral reflectance or color strength, viscosity/rheology, drying time, rub fastness, water resistance, and light fastness. Such standardized reporting would improve comparability across studies.

The third priority is to distinguish conventional and functional printing. Conventional printing requires stable and reproducible color, so unwanted pH induced shifts should be minimized. In intelligent packaging, authentication, and sensor applications, the same pH sensitivity can instead be the intended functional mechanism [8,10,17–22,25]. These applications therefore require different formulation criteria and should not be evaluated using identical definitions of stability.

Finally, stabilization technologies developed in food and film systems should be translated into printing-specific designs. Encapsulation and carrier materials can protect anthocyanins [15,16], but their effects on ink rheology, particle size distribution, nozzle or mesh compatibility, drying, and print resolution remain insufficiently studied. This represents a research opportunity at the intersection of natural product chemistry, colloid science, and graphic arts technology (Table 6).

Table 6. Research gaps and development opportunities for anthocyanin printing colorants.

Research gap	Future research direction
Limited formulation stability	Optimize pH, binder, solvent/vehicle, and copigmentation
Limited color durability data	Standardize ΔE , light fastness, water resistance, and storage stability

Limited understanding of ink substrate interactions	Compare paper types, coatings, fillers, porosity, and surface chemistry
Limited printing performance data	Evaluate rheology, transfer, drying, resolution, and printability
Environmental sensitivity	Develop controlled-response indicator and functional inks where appropriate
Insufficient chemical profiling	Combine UV–Vis with HPLC-DAD/PDA, LC-MS/MS, and NMR as needed

3.6. Limitations of the Review

The evidence base is heterogeneous because the selected literature includes direct printing experiments, natural ink formulation studies, anthocyanin stability studies, and film or smart packaging research. These sources are useful for mechanistic synthesis but do not provide identical levels of evidence for conventional printing. The review also uses a structured rather than PRISMA based systematic approach; therefore, it does not claim complete coverage of all indexed publications or provide retrospective screening statistics that were not recorded. Differences in botanical source, extraction procedure, binder system, substrate, printing method, and color-evaluation protocol limit direct numerical comparison.

A practical framework for future anthocyanin-ink studies is proposed. First, characterize the colorant, including botanical source, extraction conditions, pH response, and initial spectral properties. Second, formulate the ink using defined binder, water based vehicle, humectant, and rheology modifier and measure flow behavior and storage stability. Third, print under controlled conditions on well-characterized substrates. Fourth, quantify print performance using CIELAB, ΔE , spectral reflectance or color strength, drying behavior, and relevant fastness tests. Finally, accelerated or real-time aging should be conducted to determine whether printed color remains acceptable during the intended service period.

The distinction between demonstrated evidence and research opportunity is important. Current experimental evidence demonstrates that anthocyanin rich extracts can be incorporated into screen printing, inkjet printing, and 3D-printing systems, can produce measurable color responses, and can provide indicator or authentication functions under selected conditions. Evidence also shows that binder/matrix and substrate chemistry can modify color and stability. However, consistent color reproduction, shelf life, and printability comparable with established synthetic inks in conventional graphic production especially inkjet or high-speed printing remain insufficiently established.

3.7. Implications for Printing Technology

From a printing-technology perspective, the evidence suggests that near term applications are most compatible with processes that permit relatively viscous formulations and controlled substrate selection. Screen printing is particularly relevant because several studies have demonstrated anthocyanin-rich extracts in printing pastes or functional layers [7,8,10]. The ability of screen printing to deposit relatively thick ink layers may also be advantageous when sufficient colorant loading is required.

Inkjet printing requires tighter control of viscosity, surface tension, particle or aggregate size, filtration, nozzle compatibility, and resistance to nozzle drying. The limited direct evidence in this area should therefore be regarded as a research opportunity rather than evidence that anthocyanin inks are already technologically equivalent to conventional inkjet inks.

Packaging and labels are another relevant application area because they can exploit both coloration and controlled anthocyanin responsiveness. Conventional packaging graphics require stable, reproducible color, whereas intelligent packaging can use controlled color changes to communicate pH or product condition changes [17–22,25]. Performance specifications should therefore be defined before formulation.

Substrate properties should be incorporated into formulation design from the beginning. Paper fillers, coating, porosity, surface energy, and chemical composition can influence wetting, penetration, drying, optical scattering, and anthocyanin equilibria [1,7]. Factorial or response surface designs that include both formulation variables and substrate type can provide more informative evidence than optimization on a single substrate.

A further issue is defining acceptable color change. Decorative printing generally requires relatively tight color tolerances, whereas functional indicators require sufficiently large and reproducible color changes to be

distinguishable by users. Future studies should define acceptance criteria before testing and connect instrumental color measurements with the intended product function.

Closer integration between natural product chemistry and graphic arts engineering is therefore needed. Chemical studies can identify anthocyanin structures, degradation pathways, copigmentation effects, and protective carriers [2-6,12-16], while printing studies can determine whether those benefits persist after formulation, shear, transfer, drying, and substrate exposure [1,7-11]. Collaborative experimental designs can reduce the gap between laboratory stability studies and application-oriented print performance.

4. Conclusion

The reviewed evidence indicates that anthocyanins can be developed as natural colorants for selected printing applications, but their performance is governed by an integrated structure formulation process substrate relationship rather than pigment chemistry alone. Molecular structure and pH determine the attainable color states, while temperature, light, oxygen, moisture, and matrix interactions influence stability [2,4,5,12-17]. Direct printing studies show that extraction solvent and binder systems affect print uniformity and fastness [7], substrate chemistry can alter color expression [1], and rheological variables determine whether natural colorant formulations can be processed as inks [8,9,11].

The evidence also demonstrates an important distinction between conventional and functional printing. In conventional graphics, unwanted pH-induced color shifts and fading should be minimized. In indicators, authentication systems, and intelligent packaging, controlled color responsiveness can instead be the intended function [8,10,17-22,25]. Thus, a universal anthocyanin ink formulation is unlikely to be appropriate. Formulations should be designed for specific printing processes and applications and optimized simultaneously for pH, binder/vehicle, rheology, stabilization, substrate compatibility, CIELAB/ ΔE , drying, rub/water resistance, and light fastness.

What has been experimentally demonstrated is therefore narrower than the broad potential often attributed to anthocyanins: selected screen printing, functional printing, and 3D/4D systems have demonstrated measurable color and/or responsive functions. What remains a research opportunity includes standardized printability testing, long term color durability, broader substrate studies, chemical profiling of extracts, and validation in demanding high-speed or inkjet processes. These gaps should be addressed before broad replacement of synthetic printing colorants is claimed.

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7. Conflict of Interest

The authors declare no conflict of interest.

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