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REVIEW ARTICLE

Coumarins in applied chemical engineering: From natural scaffolds to functional materials

Yasser Fakri Mustafa*

Department of Pharmaceutical Chemistry, College of Pharmacy, University of Mosul, Mosul, 41001, Iraq

***Corresponding author:** Yasser Fakri Mustafa, Dr.yassermustafa@uomosul.edu.iq

ABSTRACT

Background: Coumarins, a class of naturally occurring α-benzopyrones, have attracted substantial interest due to their diverse structural versatility and wide range of industrial and biomedical applications. Their photophysical properties, reactive moieties, and ease of functionalization position them as valuable agents in applied chemical engineering. Aim: This review aims to comprehensively examine the role of coumarins in applied chemical engineering, highlighting their transition from natural plant-derived scaffolds to synthetic molecules with advanced functionalities for industrial and pharmaceutical use.

Methods: The article compiles and analyzes current literature on the sources, biosynthesis, and synthetic strategies for coumarins and their derivatives. It explores their physicochemical properties, functionalization methods, and implementation in diverse applications, including material science, catalysis, drug development, and environmental remediation. Results: Coumarins exhibit significant promise in various domains due to their inherent photoreactivity, electronic delocalization, and biological compatibility. Engineered coumarin-based materials have demonstrated practical utility in bioimaging, smart coatings, sensors, and therapeutic agents. The review also discusses eco-friendly synthesis techniques, recent advances in structure-activity relationships, and challenges associated with scalability and toxicity.

Conclusion: Coumarins represent a crucial intersection between natural product chemistry and modern engineering. Their multifunctionality enables them to serve as adaptable platforms for the design of next-generation materials and therapeutics. Future work should prioritize sustainable production methods, industrial scalability, and enhanced biocompatibility to unlock their full potential in applied chemical engineering.

Keywords: coumarins; chemical engineering; green synthesis; biomaterials; catalysis; drug design

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1. Introduction

In the era of advanced materials and precision-engineered functionalities, there is a growing demand for organic molecules that can serve as versatile platforms for the development of materials with tailored electrical, optical, adhesive, thermal, or magnetic properties[1]. Among these, coumarins have emerged as promising molecular scaffolds due to their unique structural features and the ease with which they can be chemically modified[2]. These small heterocyclic compounds can be transformed into complex architectures, enabling their integration into high-performance materials for applications in molecular electronics, photonics, and functional coatings[3].

Derived largely from natural sources, most notably members of the *Arabidopsis thaliana* family, coumarins are monocyclic fused-ring systems characterized by a 1-benzopyran-2-one core. Their natural origin has long inspired innovation across the pharmaceutical, cosmetic, and materials science industries[4]. In addition to being widely employed as fragrance ingredients in soaps and perfumes, certain coumarin derivatives have been used as sunscreen agents, exploiting their ultraviolet (UV)-absorbing capabilities. Notably, the conjugated π-electron system of coumarins lends them distinctive optical and luminescent properties, which has spurred interest in their use as fluorescent dyes, biosensors, and molecular probes[5].

Technological advancements in applied and green chemistry have accelerated the use of coumarins as renewable scaffolds for the design of functional materials, many of which require only brief synthetic sequences and often utilize environmentally benign or renewable feedstocks. Such sustainable synthetic strategies help reduce reliance on fossil fuel-derived reagents and minimize hazardous waste, aligning with global objectives for greener manufacturing practices[6]. Moreover, the adaptability of coumarins has led to their application in next-generation optoelectronic devices, including organic light-emitting diodes, photovoltaic cells, fluorescent particle tags, and solar energy collectors. Their incorporation into π-conjugated systems has made them invaluable in the field of advanced organic electronics[7]. In bioengineering and biomedicine, coumarin-based platforms have facilitated innovations such as near-infrared uncaging probes for targeted imaging, anisotropic fluorescent markers for live-cell tracking, and biosensors for diagnostic purposes[8].

Beyond their molecular versatility and tunable reactivity, coumarins contribute meaningfully to the growing field of functional materiomics, which aims to integrate biological relevance with engineering performance. Their multifunctionality has positioned them as cornerstone compounds for advancing interdisciplinary solutions in sustainability, healthcare, and environmental protection[9]. Looking ahead, the integration of chemical engineering principles with natural product-based chemistry offers a compelling route to accelerate the development of high-value, socially impactful materials[10]. Coumarins represent a critical link between renewable chemical platforms and emerging technologies, supporting the broader movement toward a circular, knowledge-driven economy. Their role in enabling sustainable innovations may help address the pressing need to move away from fossil-based resource exploitation and support the transition to greener, more resilient industrial paradigms[11].

2. Chemical structure and properties of coumarins

Coumarin is a relatively simple bicyclic compound characterized by a benzene ring fused to an α-pyrone ring, forming the distinctive 2*H*-1-benzopyran-2-one scaffold. The natural occurrence of coumarin was first reported in 1820 when it was isolated from the tonka bean (*Dipteryx odorata*)[12,13]. Since then, a variety of plant species have been identified as sources of coumarins, which are often responsible for the characteristic fragrance of these plants. Coumarin's sweet, vanilla-like aroma is attributed to its volatile nature, making it a popular additive in fragrances and flavorings, though its use in food products is regulated due to safety concerns[14]. Beyond its natural sources, coumarin can be synthesized through well-established chemical methods, such as the Perkin reaction, which involves the condensation of salicylaldehyde with acetic anhydride under basic conditions[15].

The parent compound, coumarin, with a molecular formula of $C_9H_6O_2$, is a colorless, fluorescent solid with a pleasant fruity scent. However, despite its appealing aroma, coumarin can be hepatotoxic if ingested in high doses, leading to concerns over its safety in consumer products[16]. Coumarin derivatives are known for a broad spectrum of biological activities, including anticoagulant[17], antimicrobial[18], and anticancer effects[19]. Additionally, their photoreactive nature under UV light has led to their classification as phototoxic agents in some contexts[20]. The electronic configuration of coumarin and its analogues plays a crucial role in their bioactivity and may also be implicated in mutagenic potential under certain conditions[21].

2.1. Natural sources of coumarins

The remarkable chemical and biological versatility of coumarins stems from their ability to form stable non-covalent interactions with a variety of biomolecules, including through intercalation and groove-binding mechanisms. These naturally occurring benzopyrone compounds have been identified in an extensive range of higher plants and certain fungi, and intriguingly, they have also been detected in the exocrine secretions and glandular tissues of mollusks[22]. Nevertheless, the most abundant natural source of coumarins remains higher plants belonging to the Apiaceae family, commonly known as umbellifers. This family includes culinary and medicinal herbs such as anise, caraway, cumin, cilantro, dill, and fennel. Additionally, coumarins are prevalent in the roots of traditional medicinal plants like *Angelica archangelica*, *Centella asiatica*, and *Levisticum officinale*, all of which have long been used in folk medicine to manage conditions such as asthma, thrombosis, and even certain types of cancer[23].

Beyond Apiaceae, coumarins are also found, though to a lesser extent, in species such as *Arachis hypogaea* (peanut), various *Citrus* species, *Cinnamomum* spp. (cinnamon), *Ginkgo biloba*, *Helichrysum italicum*, and *Peucedanum ostruthium*. Other plant families including Asteraceae, Fabaceae, Lamiaceae, Moraceae, and Oxalidaceae, along with fungal genera such as *Agaricus*, also contribute to the natural reservoir of coumarins[24]. Importantly, coumarins are not restricted to a specific plant organ; they are synthesized in leaves, stems, roots, and flowers. These compounds may exist in free form or as conjugated derivatives—such as ethers, glycosides, or esters—depending on the biosynthetic context[25]. Within plant cells, coumarins are predominantly localized in the vacuoles of chemosynthetically active exocrine tissues and the cytosol of epidermal cells. Functionally, they are classified as secondary metabolites and play a critical ecological role in plant defense, acting as chemical barriers against herbivores, insects, and microbial pathogens[26].

2.2. Synthesis of coumarins

Coumarins are highly functionalized compounds with diverse applications, making the synthesis of their derivatives a central focus in organic chemistry. Traditionally, the preparation of coumarins has relied on acid-catalyzed reactions involving 1,2-dicarbonyl compounds and phenolic substrates, most notably through the Pechmann condensation[27]. This classical method offers a broad synthetic utility, especially when using reactive 1,2-diketones such as benzyl dicarbonyls to construct carbon-rich frameworks or 3-oxoacids to access amine-containing coumarin derivatives. Despite its versatility, the Pechmann condensation often requires harsh conditions, including elevated temperatures, prolonged reaction times, and the use of toxic acidic catalysts[28].

In contrast, alternative approaches such as the Diels–Alder cycloaddition have emerged as valuable metal-free routes to coumarin scaffolds. These methods typically employ umbelliferone-based dienes or butatriene derivatives, forming oxetane intermediates that can be cleaved under basic conditions to yield the desired coumarin products. Such strategies align well with the growing demand for greener and more sustainable synthetic protocols[29]. Concerns regarding the environmental and health risks associated with metal catalysts have driven increased interest in metal-free methodologies for coumarin synthesis. Additionally, efforts have been made to diversify classical protocols by incorporating alternative Lewis acids, including lithium-based systems, to improve efficiency and selectivity under milder conditions[30]. The incoming subtitles provide a concise overview of both traditional and emerging methods for coumarin synthesis, with a particular emphasis on sustainable and environmentally conscious approaches.

Traditional methods

The synthesis of coumarins has a long and storied history in organic chemistry, reflecting their structural simplicity and biological relevance. One of the earliest and most significant methods is the Pechmann condensation, developed in the late 19th century. This classical reaction involves the acid-catalyzed condensation of phenols with β-ketoesters (such as ethyl acetoacetate) under heating conditions, typically in the presence of sulfuric acid or other Lewis acids. The simplicity, cost-effectiveness, and wide availability of starting materials make the Pechmann reaction a cornerstone in coumarin synthesis, especially for constructing 7-hydroxycoumarin derivatives such as umbelliferone. Despite some limitations regarding substitution patterns, this method remains widely used both in academia and industry[31].

Another fundamental method is the Perkin reaction, which allows the synthesis of 3-aryl-substituted coumarins. It involves the base-catalyzed condensation of salicylaldehydes with acetic anhydride or other acid anhydrides in the presence of sodium or potassium acetate. This route is especially useful for preparing coumarins with extended aromatic substitution, and it helped lay the foundation for synthesizing biologically active coumarins with increased molecular complexity. The Perkin method is particularly advantageous when the introduction of substituents at the C-3 position of the coumarin ring is desired[32].

The Knoevenagel condensation represents another classical pathway used in coumarin chemistry. This approach typically involves the condensation of salicylaldehyde derivatives with active methylene compounds such as malononitrile or cyanoacetic esters, catalyzed by weak bases like piperidine. The Knoevenagel reaction is valuable for synthesizing 3-alkyl- or 3-arylidenecoumarins, compounds known for their diverse pharmacological properties including antioxidant, anticancer, and antimicrobial effects[33].

Less frequently, the Reformatsky reaction has been applied for coumarin synthesis, particularly when α-haloesters are used with salicylaldehyde-type precursors. In this case, a zinc-mediated reaction forms a β-hydroxyester intermediate that cyclizes under acidic or thermal conditions to yield the coumarin framework. Although more complex and less commonly employed than Pechmann or Knoevenagel condensations, the Reformatsky method offers alternative substitution patterns and structural diversity[34]. **Table 1** outlines the main features of traditional methods employed in the synthesis of coumarins.

Table 1. General comparison between various traditional approaches for the synthesis of coumarins.

Method	**Key reactants**	**Catalyst / Conditions**	**Main coumarin types**	**Ref.**
Pechmann Condensation	Phenols + β-ketoesters (e.g., ethyl acetoacetate)	Acidic conditions (e.g., conc. H_2SO_4, $AlCl_3$)	7-Hydroxycoumarins (e.g., umbelliferone)	[35]
Perkin Reaction	Salicylaldehydes + acid anhydrides (e.g., acetic anhydride)	Base (e.g., sodium/potassium acetate) with heating	3-Arylcoumarins	[36]
Knoevenagel Condensation	Salicylaldehydes + active methylene compounds (e.g., malononitrile or ethyl cyanoacetate)	Weak base (e.g., piperidine) with reflux	3-Alkylidene/arylidene coumarins	[37]
Reformatsky Reaction	Salicylaldehydes + α-haloesters	Zn, acidic or thermal conditions	β-Hydroxyesters (converted to coumarins)	[38]
Method	Advantages	Limitations	Green chemistry friendly?	Ref.
Pechmann Condensation	Simple, cost-effective, high atom economy, and widely used	Limited substitution patterns and not ideal for all phenol derivatives	Partially – atom economic but uses strong acids	[39]
Perkin Reaction	Good for C-3 arylation, reliable method for aromatic substitution	Requires high temperature, long reaction time, and may produce side products	No – requires harsh conditions and generates waste	[40]
Knoevenagel Condensation	Mild conditions and allows structural diversity as well as biologically active products	May need cyclization step and not ideal for all aldehyde derivatives	Yes – mild, efficient, and solvent-flexible	[41]
Reformatsky Reaction	Unique substitution possibilities and access to complex coumarin skeletons	Less commonly used, moisture-sensitive, and more complex experimental setup	No – uses metals and generates waste	[42]

Modern synthetic approaches

In recent decades, the synthesis of coumarins has evolved significantly, moving beyond classical routes toward more efficient, environmentally conscious, and highly selective methods. Traditional procedures, such as the Pechmann, Knoevenagel, and Perkin condensations, though historically important, often require harsh conditions, prolonged reaction times, and suffer from limited substrate scope. In contrast, modern synthetic strategies aim to overcome these drawbacks through the integration of novel catalysts, greener solvents, and innovative activation techniques[43].

One of the most prominent advancements in coumarin synthesis is the use of microwave-assisted synthesis, which dramatically reduces reaction times and often increases yields compared to conventional heating. This method leverages rapid, uniform heating and is frequently applied to the Pechmann reaction, enabling the efficient construction of coumarin scaffolds under milder conditions[44]. Similarly, ultrasound-assisted synthesis has emerged as an eco-friendly alternative, enhancing reaction rates through acoustic cavitation, especially in aqueous or solvent-free media[45].

Transition-metal catalysis represents another pivotal breakthrough in coumarin chemistry. Palladium-, copper-, and iron-catalyzed cross-coupling reactions allow for precise functionalization of the coumarin core, opening the door to highly diversified derivatives with tailored biological activities[46]. For example, Heck and Sonogashira couplings enable the introduction of aryl or alkynyl substituents at specific positions of the coumarin ring, which is crucial for fine-tuning pharmacokinetic and pharmacodynamic profiles[47]. Furthermore, the rise of organocatalysis has introduced metal-free synthetic routes that rely on small organic molecules as catalysts. These methods are especially attractive for pharmaceutical applications due to their low toxicity and environmental friendliness. Organocatalyzed cascade reactions, for instance, facilitate the one-pot synthesis of complex coumarin-fused heterocycles with impressive selectivity and atom economy[48].

In parallel, biocatalytic approaches have gained attention, leveraging enzymes such as phenolases and transaminases to synthesize coumarins from natural precursors under ambient conditions. These strategies align with green chemistry principles and hold promise for sustainable industrial-scale production[49]. Lastly, flow chemistry and continuous synthesis platforms are being increasingly adopted for coumarin production. These systems provide excellent control over reaction parameters and are particularly suited for scaling up, improving reproducibility, and reducing waste[50]. **Table 2** summarized the key modern synthetic approaches used for coumarin production, highlighting their respective advantages and disadvantages. These methods reflect a shift toward more sustainable, efficient, and selective chemical processes in organic synthesis.

Table 2. The observable benefits and drawbacks of modern approaches to synthesize coumarins.

Modern method	Advantages	Disadvantages	Ref.
Microwave-assisted synthesis	– Rapid reaction times – Higher yields – Reduced solvent use	– Limited scalability – Requires specialized equipment	[51]
Ultrasound-assisted synthesis	– Eco-friendly – Enhances reaction rates – Suitable for solvent-free reactions	– Not all reactions benefit – Difficult to scale-up in industry	[52]
Transition-metal catalysis (e.g., Pd, Cu, Fe)	– High regioselectivity – Allows functionalization – Broad substrate scope	– Potential metal contamination – Cost of catalysts	[53]
Organocatalysis	– Metal-free (green) – High stereoselectivity – Biocompatible	– Often slower reactions – Limited catalyst reusability	[54]
Biocatalysis (enzyme-based)	– Mild reaction conditions – Highly selective – Environmentally friendly	– Enzyme instability – Substrate specificity limits scope	[55]
Flow chemistry	– Continuous production – Excellent control of conditions – Scalable	– High initial setup cost – Not suitable for all reaction types	[56]
Photocatalysis	– Mild and clean energy source – Access to unique reactivity	– Requires specific light sources – Often low quantum efficiency	[57]
Electrochemical synthesis	– Reagent-free redox reactions – Green and sustainable	– Requires careful optimization – Equipment cost and expertise needed	[58]

2.3. Functionalization of coumarins

Owing to their biologically active core structure, coumarins are often regarded as privileged scaffolds in the development of innovative functional materials. Functionalized coumarins, in particular, exemplify a group of nature-inspired molecules that offer cost-effective and environmentally sustainable alternatives to conventional synthetic compounds. These derivatives can often be synthesized from abundant, renewable sources, making them attractive candidates for greener chemical processes[59]. To enhance the functional diversity and application potential of coumarins, a wide array of organic synthesis strategies has been explored. These methods enable either broad functionalization across the coumarin nucleus or selective modification at specific molecular sites[60]. Such modifications not only improve the known properties of coumarins but also pave the way for entirely new functionalities. The resulting compounds have shown significant promise in applied fields including biomedicine, optoelectronics, catalysis, and the development of dye-sensitized solar cells[61].

Despite some limitations associated with the natural distribution, bioavailability, and metabolic fate of coumarins, synthetic approaches offer a means to overcome these challenges. The design and synthesis of novel functionalized coumarins allow for tailored physicochemical and biological profiles, improving their suitability for specific technological and therapeutic applications[62].

Recent advancements in synthetic chemistry have provided an expanded toolkit for coumarin functionalization. Traditional electrophilic substitution reactions remain in use, but they are increasingly complemented by more refined methodologies such as catalytic cross-couplings, cycloaddition reactions, and other modern synthetic transformations[63]. Among these, bioorthogonal chemistry has gained particular attention. These reactions—characterized by their high selectivity, mild conditions, and compatibility with aqueous and solvent-free environments—facilitate the creation of coumarin-based libraries suitable for biological screening[64]. Their biocompatibility allows for *in vitro* and preclinical evaluation of these compounds without extensive modification or purification steps, thereby accelerating the discovery of functional materials with real-world applicability[65].

Modification techniques

Naturally occurring coumarins serve as versatile molecular scaffolds that can be readily modified to yield a wide array of biologically active derivatives. Various synthetic approaches have been developed to tailor the coumarin backbone, where strategic modifications at specific positions can enhance pharmacological properties, improve molecular stability, and expand chemical functionality. These structural changes significantly broaden the application potential of coumarin derivatives, making them valuable not only in pharmaceutical development but also in the specialty and commodity chemical industries[66].

Many coumarin-based compounds feature phenolic hydroxyl groups, and in synthetic procedures, these functionalities are often protected when not directly involved in subsequent transformations. Common synthetic modifications, as illustrated in **Figure 1**, include etherification, esterification, acylation, halogenation, nitration, oxidation, amidation, and ring-opening reactions, most of which can be conducted using straightforward laboratory techniques[67].

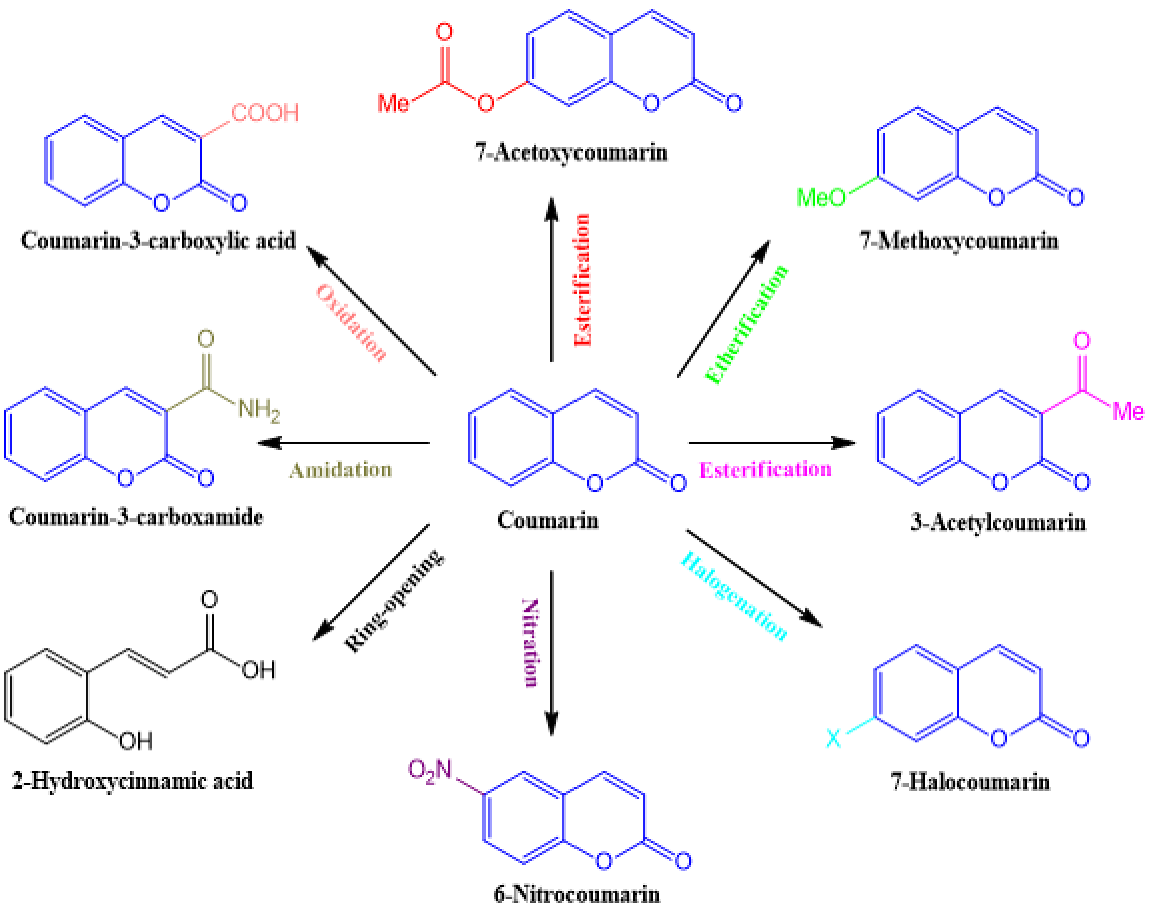

Figure 1. Common structural modification strategies of the coumarin core, which is in blue.

Among these, acylation remains a prominent modification strategy for simple coumarins, typically achieved using mixed anhydrides such as acetic anhydride to obtain acylated products at the C3 position[68]. Additionally, classical Michael addition reactions are frequently employed to introduce substituents at the C3 and C4 positions. Other C3-functionalization methods include coupling reactions with diazo compounds, thioketones, or isothiocyanates, as well as the construction of diverse heterocyclic systems like thiazoles, oxadiazoles, and thiophenes[69]. Moreover, the coumarin core can be further diversified through hydroxylation, amination, and chloroalkylation, enabling the incorporation of varied functional groups. These derivatives may also be connected using conventional linking strategies to generate more complex molecular architectures[70].

Finally, esterification reactions play a crucial role in modifying coumarin-based molecules by targeting their hydroxyl (–OH) or carboxyl (–COOH) functional groups. Through the formation of ester linkages, the chemical properties of coumarins—such as lipophilicity, membrane permeability, and metabolic stability—can be significantly improved. This modification is particularly valuable for enhancing bioavailability or enabling prodrug design. The choice of esterification strategy largely depends on the specific substitution pattern of the coumarin core, such as in hydroxycoumarins or carboxycoumarins, allowing for a variety of ester derivatives to be synthesized based on the desired pharmacological or physicochemical properties[71]. Also, several types of esterification reactions are possible, as recorded in **Table 3**.

Table 3. Coumarin esterification toolbox: Reaction conditions, catalysts, and functional group targets.

Reaction type	**Reagents/Conditions**	**Target group / Purpose**	**Ref.**
Phenolic esterification	R–COOH or R–COCl; acid/base catalyst (e.g., H_2SO_4, pyridine)	Esterifies –OH at C7, C6, or C8 (e.g., umbelliferone derivatives)	[72]
Fischer–Speier esterification	Carboxylic acid + alcohol; acid catalyst (HCl, H_2SO_4); heat	Converts coumarin-3-carboxylic acid to esters	[73]
Steglich esterification	R–COOH, DCC, DMAP; mild, room	Esterifies phenolic –OH without harsh	[74]

Reaction type	Reagents/Conditions	Target group / Purpose	Ref.
	temperature	conditions	
Acyl chloride esterification	R–COCl; base (e.g., TEA, pyridine)	Rapid esterification of phenolic hydroxyl groups	[75]
Transesterification	Ester + alcohol; acid/base catalyst or enzymes	Converts existing ester to another via alkoxy exchange	[76]
Enzymatic esterification	Lipase or esterases; often in organic solvent or ionic liquids	Green synthesis; regioselective esterification of –OH	[77]

Table 3. (*Continued*)

Applications of functionalized coumarins

Functionalized coumarins possess a rich array of properties that arise from the interplay between the inherent photophysical features of the coumarin core and the modifications introduced by functionalization. These molecular hybrids have found diverse applications in materials science and photonic technologies, as displayed in **Figure 2**, serving as key components in dyes, light-emitting materials, photostabilizers, chemosensors, and devices based on non-linear optics[78]. While this subsection provides select examples to illustrate the versatility of modified coumarins, it does not aim to offer an exhaustive review of their use across all systems.

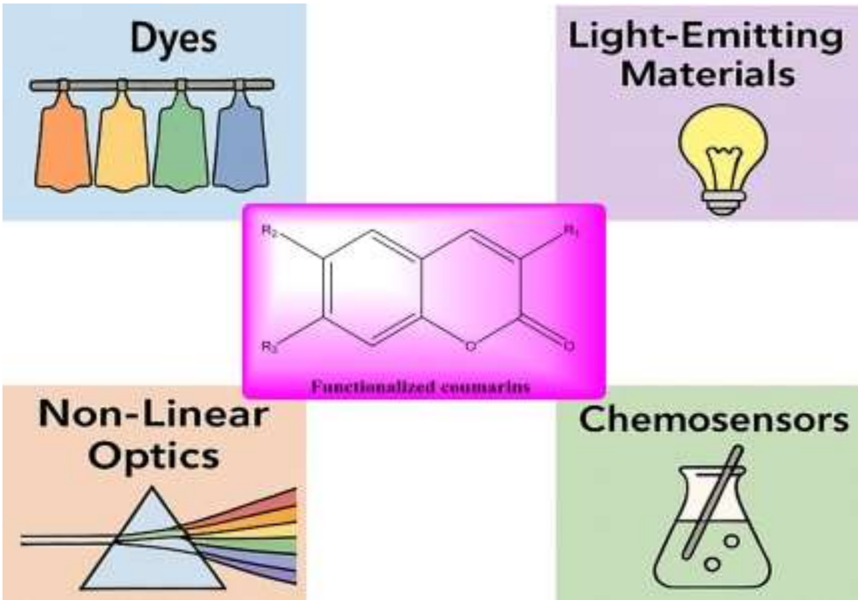

Figure 2. Some non-medical applications of functionalized coumarins.

Historically used as natural dyes, coumarins have retained their relevance in modern industries due to their strong light absorption and emission characteristics. Today, they are incorporated into synthetic dye formulations for textiles (e.g., cotton fabrics), as well as in coloring agents for plastics, gelatin capsules, waxes, and related materials. Structural modifications to the coumarin scaffold have significantly enhanced these properties. For instance, novel fluorescent dyes have been synthesized through amide bond formation involving 7-aminoethylcoumarin-4-acetic acid. Other advancements include highly emissive derivatives based on 4-carboxycoumarin and 4-carboxycoumarin-6-sulfonic acid[79].

Beyond traditional dyeing applications, functionalized coumarins have inspired the design of artificial photosensitizers and advanced optoelectronic systems. These compounds are being explored for use in photodynamic therapy, as photoinitiators in polymer chemistry, and in solar energy conversion via photovoltaic and photocatalytic pathways. One noteworthy example includes the development of coumarin–imidazoacridinone hybrids capable of targeting double-stranded DNA with potential anticancer activity[80]. Another promising strategy involves fluorocoumarin derivatives bearing N-propynyl groups, which have shown the ability to generate emissive triplet states via thermally activated delayed fluorescence[81]. In addition, research has advanced toward the creation of electroluminescent and fluorescent materials using functionalized coumarin backbones. For example, polymers incorporating hydroxyphenyl moieties and 7-hydroxyphenyl-4-boryl-coumarin units have been synthesized through phosphane polymerization. These materials demonstrate electrical and optical activity, making them promising candidates for the development of next-generation light-emitting films[82].

2.4. Coumarins in material science

A wide range of coumarin-based materials, particularly polymers and composites, have been developed owing to their attractive optical and electronic properties. For instance, coumarin-containing polyamides can be synthesized as either soluble or insoluble films and are characterized by high glass-transition temperatures. When coumarin chromophores are covalently attached to the polymer backbone, their UV–visible absorption spectra can be finely tuned by adjusting the coumarin content[83]. Hybrid copolymers composed of poly(ethylene terephthalate) and poly(ethylene oxide) segments, with coumarin moieties functioning as photo-responsive crosslinking sites, have also been reported. These materials exhibit a well-ordered lamellar morphology and high degrees of crystallinity, particularly at low coumarin loadings. Upon UV irradiation, the coumarin units undergo crosslinking reactions, resulting in significant changes in the materials' optoelectronic characteristics[84].

Additionally, coumarin-based polymers exhibiting excellent thermal stability and resistance to UV degradation have been developed, making them suitable for protective coatings. Certain coumarin-functionalized copolymers have shown promise in nanostructured light-emitting diode applications due to their high fluorescence quantum yields combined with favorable topological and mechanical stability[85]. Tailoring the side chains of coumarin-functionalized liquid crystalline polymers has allowed for tunable solid-state emission profiles upon UV excitation. In one approach, coumarin side-groups were covalently bound to diamine-based crosslinkers and subsequently reacted with polyisocyanate soft segments to produce flexible polyurethane films. These materials serve as eco-friendly adhesives, offering both durability and recyclability[86].

More advanced coumarin-containing polymer systems have been created by integrating solar-active nanoparticles. One example involves the encapsulation of 2.6 nm cadmium selenide quantum dots within a block copolymer matrix bearing both coumarin and azobenzene functionalities. These nanocomposites exhibit reversible photoinduced molecular orientation, with the quantum dots acting as spatial markers of the resulting nanostructures[87]. Another example features a binary nanocomposite consisting of a coumarin-modified polystyrene azopolymer doped with ~30 nm silver nanoparticles. This system demonstrated enhanced physicochemical properties and potential applications in photovoltaic energy harvesting[88].

Polymers and composites

In recent years, the pursuit of sustainable and biodegradable materials has intensified, particularly for use in packaging, agriculture, and biomedical applications. Coumarins have emerged as promising candidates in the development of novel bioplastic materials, largely due to their structural versatility and capacity for functional modification through various chemical and polymerization approaches[89]. One notable strategy involves the oxidative polymerization of bifunctionalized coumarins, catalyzed by laccase enzymes, which results in the formation of biopolymer films. These films benefit from the conjugated systems present in the resulting polymers, such as poly(3,4-ethylenedioxy-6-nitrophenol), which endow them with distinct optical properties[90]. Furthermore, microwave-assisted and sonochemical polymerization techniques have been successfully employed to synthesize coumarin-based polymers and copolymers, offering materials with potential utility in the optical coatings industry due to their enhanced photophysical characteristics[91].

Beyond homopolymers, coumarin has also been co-polymerized with established polymers like poly(vinyl alcohol) (PVA) and poly(methyl methacrylate) to produce films with desirable degradability and functional performance. In another innovative example, a hybrid phosphorescent material was fabricated by integrating coumarin-functionalized moieties with PVA and chitosan/silica aerogel matrices. These hybrid films exploit the aerogel's properties, such as porosity and UV responsiveness, making them suitable for applications in UV light detection[92]. Coumarin derivatives have also been incorporated into polylactic acid (PLA)-based systems. For instance, composite films containing 8-hydroxy-4-methylcoumarin and 7-acetoxy-4-methylcoumarin demonstrated both fluorescence quenching and delayed photoemission effects. Importantly, these composites showed improved biodegradability compared to neat PLA, highlighting coumarin's potential in enhancing environmentally friendly polymer technologies[93].

Advancements have also been made in the creation of coumarin-functionalized silica nanoparticles embedded within PLA matrices, resulting in materials with novel functional characteristics[94]. Further, a light-emitting nanocomposite device was developed using europium oxide and diphosphine oxide phosphor-decorated silica nanoparticles in combination with silver nanoparticles functionalized with coumarin-glycidyl methacrylate moieties[95]. In photovoltaic applications, coumarin has even been integrated into ceramic–polymer hybrid layers within perovskite solar cells, where it plays a role in improving both surface treatment and overall device performance[96].

Nanomaterials

Since the identification of 3-(2-benzothiazolyl)-7-diethylaminocoumarin as an effective agent in the hydrothermal synthesis of ZnO nanowires, the incorporation of coumarin derivatives into inorganic frameworks has gained significant attention. These compounds have found applications as pore-directing agents in the template-assisted fabrication of mesoporous silica, as multifunctional additives in bioactive and photoluminescent CuO–$CaTiO_3$ composites, and as key building blocks in the design of porous, luminescent, and hydrophilic metal–organic frameworks (MOFs) based on Zn(II) and Cd(II)[97]. Notably, the covalent integration of 3-(2-benzothiazolyl)-7-diethylaminocoumarin (**Figure 3**) as a bridging ligand with Zr_6 secondary building units led to the formation of a zirconium-based MOF that exhibits strong photoluminescent properties and is capable of detecting small molecules such as acetone with high sensitivity[98]. In another application, coumarin moieties were employed as pendant functional groups, allowing facile postsynthetic modification with amines. This approach enabled the creation of Zn(II)-based hybrid materials with enhanced hydrogen storage capacity[99].

Moreover, leveraging the photophysical characteristics of lanthanide ions, researchers have developed a porous europium–aluminium MOF where coumarin acts as a light-harvesting antenna to sensitize f–f transitions of the europium centers. A separate MOF system featuring integrated 3-carboxyethylcoumarin (**Figure 3**) demonstrated effective fluorescence-based sensing of hypochlorite ions[100]. Beyond MOFs, coumarin-based conjugated polymers have been explored as chemosensory materials for detecting halides, peroxides, and heavy metal ions. These polymeric films exhibit superior sensing capabilities compared to their monomeric counterparts, highlighting the broad potential of coumarins in the field of materials science and environmental monitoring[101].

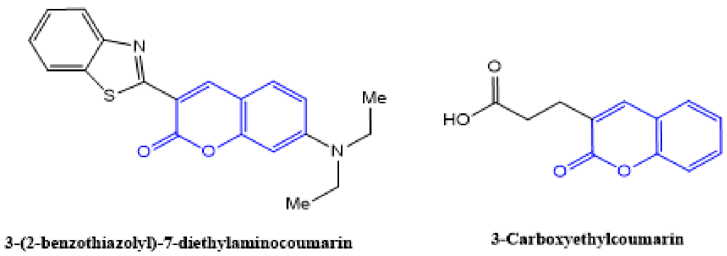

Figure 3. Chemical structures of key coumarins for the development of nanomaterials.

2.5. Biological activities of coumarins

Numerous coumarin derivatives have demonstrated promising pharmacological effects across various therapeutic domains, including oncology, infectious diseases, inflammatory disorders, and bone-related conditions such as osteoporosis[102–104]. Their favorable attributes—such as generally low toxicity, straightforward synthetic accessibility, and the ability to tailor their chemical structures for enhanced efficacy—make these derivatives particularly attractive as scaffolds for drug discovery and development[105–107].

Antimicrobial properties

The growing concerns over synthetic preservatives and their potential side effects have sparked a global interest in identifying safer, more natural alternatives. As a result, there is increasing scientific attention toward the biological potential of natural products. Among these, coumarins have emerged as promising agents, particularly for their selective antibacterial and antifungal activities[108]. Numerous studies have demonstrated that coumarin derivatives possess noteworthy efficacy against a broad spectrum of gram-positive and gram-negative bacteria. Moreover, some derivatives have shown remarkable inhibitory effects against *Mycobacterium tuberculosis*, indicating their potential in managing mycobacterial infections[109]. Recent research also highlights the relevance of coumarin-rich plant extracts in addressing human dysbiosis, especially conditions associated with imbalances in lactic acid bacteria and bifidobacteria populations. In light of the escalating resistance to conventional antibiotics, integrating coumarins into modern therapeutic strategies is gaining traction[110].

Innovative and environmentally friendly methods for synthesizing nanomaterials are further expanding the applicability of natural antibacterial agents such as coumarins. However, nanomaterials often face challenges related to stability and selectivity. Thus, combining nanomaterials with bioactive compounds like coumarins offers a synergistic approach to enhance antimicrobial efficacy, particularly in tackling resistant strains and bacterial biofilms—a common concern in clinical settings[111]. Given the growing limitations of traditional antibiotics in both medical and food preservation contexts, exploring coumarin-based alternatives presents a valuable path forward. These natural compounds, especially when used in conjunction with nanotechnology, hold promise for safer, more sustainable antimicrobial interventions[112–114].

Antioxidant activities

Antioxidants are bioactive molecules that inhibit or slow down oxidative reactions, thereby protecting cellular components from damage induced by reactive oxygen species and other free radicals. In humans, the antioxidant defense system operates through two primary mechanisms: enzymatic antioxidants (such as superoxide dismutase, catalase, and glutathione peroxidase) and non-enzymatic antioxidants (including vitamins C and E, glutathione, and various polyphenols)[115]. However, excessive exposure to environmental pollutants, radiation, certain drugs, and unhealthy lifestyles can lead to elevated reactive oxygen species production, surpassing the body's ability to neutralize them effectively. This imbalance results in a condition known as oxidative stress[116].

Oxidative stress plays a central role in the disruption of cellular homeostasis, often involving iron dysregulation, and contributes to the onset and progression of various pathological conditions. These include diabetes mellitus—where protein glycation and reactive oxygen species production are key factors—along with irreversible modifications of lipids, nucleic acids, and proteins[117]. Additionally, oxidative stress is implicated in ischemia–reperfusion injuries, neurodegenerative disorders such as Alzheimer's and Parkinson's diseases, carcinogenesis, chronic infections, immunodeficiency syndromes, and complications in organ transplantation including graft rejection[118]. Given these associations, there is a growing interest in developing effective and safe antioxidant agents for both medical and industrial applications. Among the promising candidates are coumarins that have attracted significant attention due to their potent antioxidant properties[119].

Over the past few decades, numerous studies have demonstrated the *in vitro* and *in vivo* antioxidant potential of various coumarin derivatives. The structural versatility of the coumarin scaffold allows for extensive chemical modifications, which can enhance their biological efficacy[120]. Notably, electrophilic substitutions at positions C-3 and C-7 of the coumarin ring system have enabled the introduction of alkyl and aryl groups, tailoring their antioxidant activity. Furthermore, recent advances include the incorporation of N-alkyl and N-aryl substituents at the 3-position of the benzopyran-2-one core, as well as O-alkylation of hydroxyl groups at position C-7[121]. These modifications have significantly advanced our understanding of structure–activity relationships, offering new avenues for designing coumarin-based antioxidants with enhanced therapeutic potential[122].

Potential in drug development

There are hundreds of reviews dealing with coumarin biological activities although none summarize the entirety of coumarin's potential in drug development. More than 70 coumarin-derived drugs, as shown in **Figure 4**, and herbal formulations are currently used in clinical practice or have been investigated in clinical trials. Although these coumarin-derived drugs come from medicinal plants and their metabolites, the mechanisms of their main bioactivities are poorly understood[123]. Some of these drugs have proven to be effective, such as a specific compound which is an inhibitor of tumor growth and invasion of cancer in nude mice[124]. Despite the known potential biological activities of coumarins, there are still some gaps between research and practical application, and many obvious specific adjuvant mechanisms remain unfound.

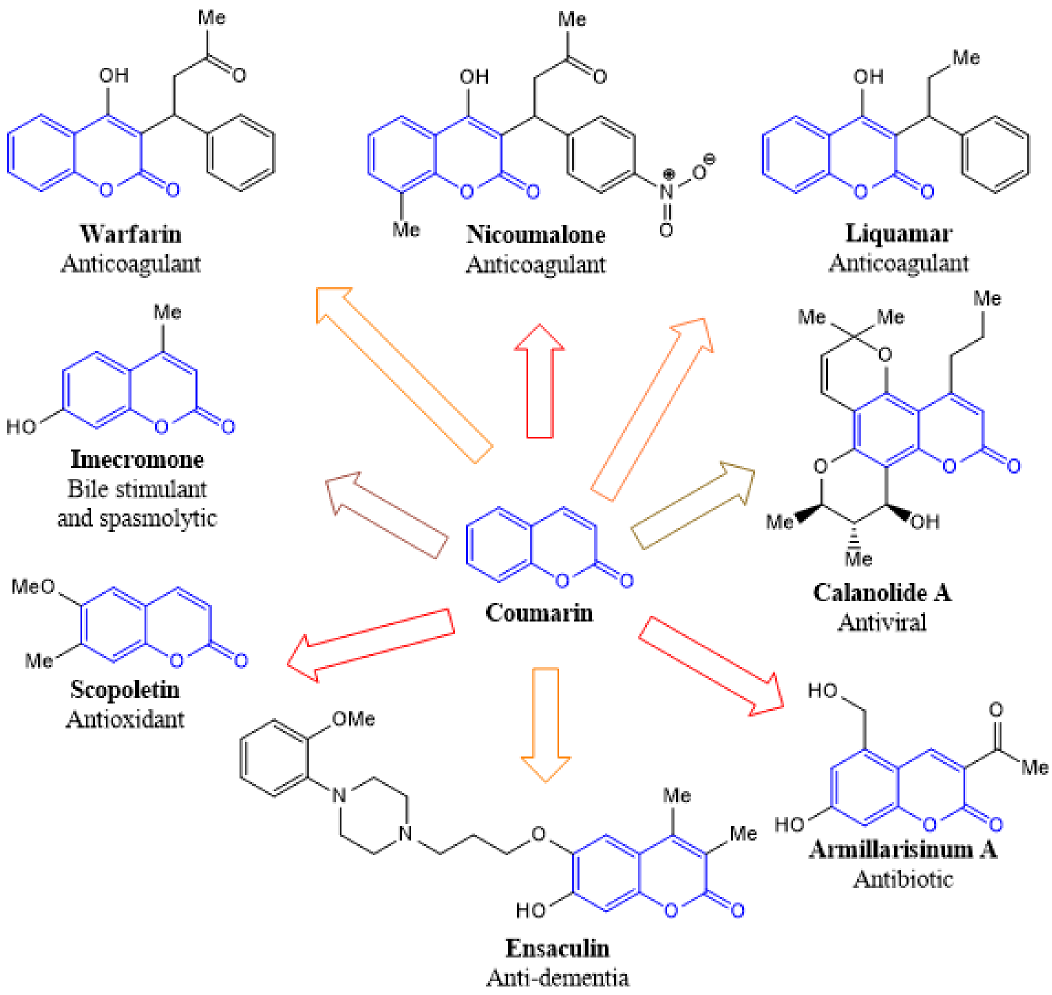

Figure 4. The chemical structures of several coumarins that are currently in the clinical in-hand.

Besides achieving more specific compounds to elucidate and determine mechanisms for the different activities of coumarins, overcoming limitations in bioavailability or efficacy should also become a priority.

Recently, several studies have suggested that the combination of different drugs or therapeutic strategies is the best way to beat a malignant disease[125]. Drug plasmid, anticancer peptide, oligonucleotide, or combination treatment with some chemotherapeutic drugs and photodynamic therapy or photoimmunotherapy may prove effective[126]. These tools can be combined with the inhibitory property of coumarins. Innovative approaches to enhance the permeability and bioavailability are also the way to improve coumarin potential. Coumarins have promising potential as adjuvant molecules alone or in combination with other drugs or therapeutic methods[127]. Further studies should be carried out to bring the use of coumarins for drug formulation into clinical practice.

2.6. Coumarins in environmental applications

Although coumarins have historically been viewed with caution due to their toxicological properties, these same characteristics have recently been harnessed for beneficial applications, particularly in environmental protection. Emerging research suggests that coumarin derivatives possess promising potential in the field of bioremediation[128]. Several compounds within this class have demonstrated the ability to inhibit the proliferation of soil-borne pathogenic bacteria, thereby contributing to the restoration of microbial balance in contaminated environments[129]. Additionally, coumarins have been shown to reduce the concentrations of heavy metals and sulfate residues in polluted water systems, indirectly supporting the activity of native microorganisms involved in ecological cleanup[130].

Beyond bioremediation, coumarins are gaining attention for their role in the development of environmentally friendly antifungal coatings. For instance, coatings formulated with coumarin monoesters, some of which exhibit local anesthetic properties, have demonstrated effective resistance to fungal colonization on wooden surfaces, while also maintaining visual appeal and user safety[131]. Similar outcomes have been observed in antifungal wall coatings, where coumarin-containing compounds not only reacted with atmospheric moisture to release fungicidal agents but also enhanced the hydrophobicity of the treated surfaces, thereby improving their durability and performance[132–134].

The utility of coumarins extends further into the creation of advanced functional materials. By chemically coupling coumarins with various construction substrates, researchers have developed photocatalytic systems capable of degrading airborne and waterborne pollutants[135]. Moreover, coumarins have been incorporated into bio-based, photostable, and superhydrophobic coatings for outdoor wooden structures. These coatings not only hinder microbial colonization but also promote self-cleaning properties, extending the longevity and cleanliness of the materials[136].

Recent innovations also highlight coumarins as key components in eco-friendly hybrid coatings designed for use on ceramic surfaces. For example, coumarin-based treatments applied to red clay tiles have been shown to significantly enhance oleophobicity, particularly when combined with slippery liquid-infused porous surface technology[137]. Such modifications offer a sustainable and economically viable route to improving the environmental performance of construction materials, underscoring the evolving importance of coumarins in green chemistry and sustainable material science[138].

The quest for sustainable practices, especially in industrial-scale applications, has encouraged the exploration and the use of green alternatives; among them the essential oils used in the synthesis of coumarin-based materials stand out. They are bio-based molecules coming from plants that usually have a lower toxicity and low environmental impact, a renewable character, a degradability, and a wide availability of species[139]. In addition, due to the enormous variety of existing chemical species, they can easily be complemented or combined with other precursors to generate products with superior features. These bio-based materials fit perfectly within the principles of green chemistry and are of interest in industries such as cosmetics and personal care products, biomedical, food packaging, coatings, and agrochemical, especially against phytopathogens[140].

Eugenol, an aromatic compound naturally present in clove, cinnamon, and bay-stem essential oils, was incorporated to a PLA matrix to generate a new composite blend with improved biodegradable properties. This polymer is a thermoplastic polyester soluble in organic solvents; however, its use as a food packaging material and biomedicine scaffold is limited due to its brittle and hydrophobic nature, which favors superficial cracks development and poor compatibility with aqueous and/or alcoholic foods[141]. The results showed that eugenol/PLA composite films proven to be more resistant to UV-Vis radiation than PLA alone; in addition, the presented contact angle values indicated that incorporation of eugenol to PLA increased its hydrophilicity, generating a significant impact when applied in active food film packing. In turn, eugenol's film-forming behavior was highlighted by its potential to provide the new composite with antimicrobial characteristics. This indicates that the developed composite may combine the functional "active packing" properties with biodegradable potential for the packaging industry[142].

2.7. Industrial applications of coumarins

Coumarin and its derivatives have garnered significant attention across various industries due to their multifaceted biological and chemical properties. Their applications span drug discovery and development, the fragrance and flavor industries, and the production of agrochemicals[143]. The global pharmaceutical and natural product sectors collectively generate revenues exceeding US$3 trillion, reflecting a growing demand for safe, naturally derived compounds with minimal adverse effects. Within this context, coumarins have demonstrated promising potential, particularly as therapeutic agents[144].

Historically, coumarins have been utilized in traditional medicine for the treatment of infectious diseases. Modern research has confirmed that over 75 coumarin-based compounds exhibit notable anticancer activity in both *in vitro* and *in vivo* models. Additionally, more than 50 derivatives have shown anti-HIV activity, with some currently progressing through clinical trials as potential candidates for HIV therapy[145]. Beyond therapeutic uses, coumarins have long been appreciated for their aromatic and sensory qualities. Natural coumarins were traditionally used in perfumery and flavoring, and advancements in analytical technologies have since revealed the vast diversity and abundance of coumarins in nature. These compounds contribute to the scent and taste profiles of various personal care products, including soaps, body butters, and sugar scrubs. Since the 19th century, both natural and synthetic coumarins have played integral roles in the fragrance and cosmetic industries. Extracted from the leaves of many tropical medicinal plants, coumarins are valued for their pleasant scent and invigorating effects. Synthetic coumarin remains widely employed as a cost-effective fragrance enhancer[146].

Coumarins are documented to be allelopathic agents acting as herbicides in several plant species. Their actions against phytopathogens further qualify these compounds and other chemical derivatives like agrochemicals with fungicide action, which are essential products globally. Due to the increasing demand for safer production technologies and greener crops, research has been concentrated on the identification of natural phytopathogen inhibitors, as they can be more environment-friendly and promote the control of disease pathogens[147]. Additionally, they can assist in resistance management to prevent the incidence of resistance development in some fungal species to commercial chemical fungicides. Coumarin and other derivatives have been investigated regarding their capability to inhibit plant pathogens and promote plant growth. Compounds procumbide and ewine, isolated from *Mandevilla velutina*, proved to be promising agents for plant protection due to their antimicrobial properties, being potent inhibitors of *Fusarium solani* and *Rhizoctonia solani* fungus[148].

2.8. Future perspectives on coumarins

Coumarins have long held a significant place in applied research and various industrial sectors. However, the emergence of new technologies is rapidly transforming the landscape of chemical synthesis, opening the door to innovative transformations that were once considered unfeasible. As synthetic chemistry becomes increasingly integrated with fields such as advanced materials science, catalysis, medicine, energy, artificial intelligence, and neuroscience, the exploration of coumarins is poised to expand across these interdisciplinary boundaries. In recent years, coumarins have gained renewed attention not only as versatile molecular scaffolds but also as functional building blocks in the design of advanced materials and catalytic systems. Their unique photophysical and chemical properties make them particularly suitable for applications in smart materials, optoelectronics, and as organocatalysts in key transformations. This trend is expected to accelerate as more research converges at the intersection of chemistry, materials science, and biotechnology.

Moreover, advances in metabolic engineering and synthetic biology are reshaping how coumarins can be sustainably produced. The ability to design, assemble, and evolve biological systems has enabled the development of bioengineered platforms for the efficient and scalable biosynthesis of diverse coumarin derivatives. These systems, often based on microbial hosts, allow for greater flexibility in producing structurally complex and otherwise rare coumarin analogs with higher yields and reduced environmental impact. Such biotechnological approaches not only enhance access to novel coumarin scaffolds but also hold promise for the discovery and development of new pharmacologically active compounds. As part of the ongoing shift toward greener and more sustainable chemistry within the framework of the Fourth Industrial Revolution, coumarins stand out as a valuable resource for both innovation in drug discovery and the development of functional materials with broad industrial relevance.

Emerging technologies

It is estimated that more than 80% of future breakthroughs in chemistry will arise from the integration of cutting-edge technologies with sustainable engineering principles. Within this context, the drive to replace traditional chemical processes with environmentally benign alternatives is strongly aligned with the core philosophy of green chemistry. This paradigm is fueling intense research across multiple subfields of chemistry, including organocatalysis, flow chemistry, solar energy conversion, ionic liquids, mechanochemistry, electrochemistry, photochemistry, microwave-assisted synthesis, information technology, miniaturization, nanoscale systems, and artificial intelligence.

One promising direction is the development of new materials rooted in the concept of sustainable innovation. By utilizing secondary metabolites from plant-based feedstocks, researchers can design eco-efficient, biocompatible, and biologically active materials. These natural resources provide a renewable foundation for the creation of next-generation functional compounds. In parallel, unbiased approaches to discovering novel chemical entities are also gaining momentum. The integration of computational modeling with fast, cost-effective synthesis, early-stage biological screening, and re-synthesis of lead candidates enables the efficient generation of novel molecular libraries. This approach holds significant promise for the textiles, food, and cosmetics sectors, where demand for sustainable and bioactive ingredients is growing.

Research directions

Coumarins have long held a prominent role in industrial applications, owing to their diverse chemical structures and wide range of functional properties. The remarkable versatility of coumarin derivatives continues to drive innovation across multiple sectors, enabling their integration into increasingly specialized and technologically advanced systems. In recent years, scientific attention has steadily shifted toward the design and development of coumarin-based functional materials and smart devices, marking a significant evolution in their application landscape. Despite their long-standing use, many aspects of coumarin chemistry remain underexplored. Research groups worldwide are actively investigating novel synthetic strategies, structural modifications, and multifunctional properties of coumarin derivatives to unlock their full potential. With continued progress in materials science and nanotechnology, the next decade is anticipated to witness transformative advancements in coumarin-based technologies. These developments align closely with the global agenda for sustainable innovation, particularly in support of the United Nations' 2030 Sustainable Development Goals.

To achieve this vision, future research must focus on several key areas. These include a deeper understanding of the structural and dynamic behavior of coumarins; the fabrication and characterization of coumarin-based thin films; the exploitation of non-covalent interactions in nanostructured coumarin systems; and the discovery of new sensory and chiroptical phenomena. Additionally, coumarin scaffolds hold promise for emerging applications such as organic photovoltaics, molecular sensing, bioactive conjugates, data storage technologies, and environmentally responsive materials.

One particularly promising avenue involves the construction of multi-layered materials using coumarin derivatives—either homogenous stacks or hybrid assemblies—which are already feasible using coumarin-containing polymers. The structural diversity and chemical tunability of these compounds pave the way for innovative layer-by-layer architectures with tailored properties. In conclusion, while coumarin-based research has made significant strides, it remains a fertile ground for discovery and application. Continued interdisciplinary collaboration will be essential to fully harness the potential of these fascinating molecules across materials science, environmental engineering, and sustainable technology domains.

2.9. Challenges in coumarin research

Despite the remarkable versatility and promising biological activities of coumarins, research and development in this field still face notable limitations. One of the primary challenges lies in the synthetic accessibility of structurally diverse coumarins. Although a wide range of classical organic reactions are available for coumarin synthesis, many of these traditional methods fall short when evaluated under the principles of green chemistry, particularly with respect to sustainability, atom economy, and environmental safety.

The most commonly employed method—Knoevenagel Condensation—though efficient, often leads to side products such as isocoumarins and coumarins bearing non-target substituents. This limits the overall yield and purity of desired products. Additionally, when more complex substitution patterns are required, especially for introducing multiple groups on the coumarin ring system, multistep and costly synthetic strategies are often needed. These processes are typically feasible only within specialized fine chemical laboratories, which may not be accessible for all researchers.

Another limitation encountered at the commercial level is the restricted availability of coumarin derivatives from fine chemical suppliers. Many suppliers offer only a limited range of substituted coumarins, especially those bearing hydroxyl or methoxy groups—functional moieties that are essential for enhancing antioxidant and photoprotective properties. This scarcity of structurally varied analogs can hinder both exploratory research and the development of coumarin-based molecules tailored for specific applications, including those in pharmaceuticals, cosmetics, and photoprotection.

Synthesis limitations

Despite the wide utility and structural diversity of coumarins, several challenges persist in their chemical synthesis. Traditional methods, such as the Pechmann condensation, Knoevenagel reaction, and Perkin synthesis, though historically significant and still in use, often suffer from various drawbacks that limit their broader application, particularly in industrial or environmentally sensitive contexts. These methods frequently require harsh reaction conditions, including strong acids or bases, high temperatures, and extended reaction times, which may reduce selectivity and compromise product purity.

Another major limitation lies in the narrow substrate scope of conventional routes. Many synthetic protocols are highly sensitive to the electronic nature and steric hindrance of the starting materials, especially phenols and aldehydes. This restricts the ability to introduce diverse substituents at key positions on the coumarin ring, particularly at the C-3, C-4, and C-8 positions. As a result, the synthesis of coumarins bearing multiple or unusual functional groups often becomes cumbersome or inefficient, requiring lengthy multi-step sequences that are time-consuming and resource-intensive.

Furthermore, yields from traditional methods can be inconsistent and often low, especially when working with substituted or sterically hindered substrates. This inefficiency becomes especially problematic when scaling up for pharmaceutical or industrial applications. Additionally, many classical reactions generate considerable waste, rely on toxic reagents or solvents, and may require chromatographic purification steps, raising significant environmental and safety concerns.

Finally, reproducibility and selectivity in the synthesis of chiral coumarin derivatives remain challenging. The lack of stereoselective approaches limits access to enantiomerically pure compounds, which are essential in medicinal chemistry due to the profound influence of chirality on biological activity. In light of these issues, there is a growing need for innovative, sustainable, and more selective synthetic strategies—such as those involving enzymatic catalysis, green solvents, or photochemical methods—to overcome the current limitations and unlock the full potential of coumarin chemistry. Overall, this discussion integrates conventional and green chemistry perspectives to provide a comprehensive view of current challenges and future directions in the sustainable synthesis of coumarin derivatives.

Market barriers

Given the chromophoric potential of coumarin-based structures and the growing demand for sustainable, non-fossil-derived ingredients, one might anticipate a broad commercial presence of coumarin derivatives across the flavor, cosmetic, and pigment industries. However, this expectation remains largely unmet. Despite their advantages—such as reduced carbon footprint, favorable biocompatibility, non-toxic biodegradability, and improved solubility in polar solvents—plant-derived coumarins are rarely used in substantial amounts, particularly in fruit flavorings and additives. This limited utilization stems from multiple market-level barriers that hinder widespread adoption. Overcoming these challenges is essential to unlocking the full potential of coumarins in industrial applications. Historically, the rise of petroleum-based mass production, exemplified by synthetic vanillin, demonstrates a similar pattern. Initially, natural flavor compounds were scarcely offered, and synthetic analogs, often supported by plant descriptions with comparable sensory profiles, dominated the market. Only when synthetic production scaled up and became economically competitive did synthetic vanillin gain substantial market share. Nevertheless, the proportion of natural vanillin remained relatively constant.

A comparable situation exists with coumarins, particularly in applications leveraging their optical properties. Although coumarins are synthesized in large quantities for research and specialized uses, they have not achieved significant integration into mainstream commercial products. For instance, despite the successful introduction of natural alternatives to synthetic safety dyes, coumarins are notably absent from dyes intended for ophthalmic applications. Similarly, in sectors such as fluorescent whitening agents for plastics or organic coating materials, coumarins remain underutilized. Even though the dyeing mechanisms involved in these applications closely resemble those used for larger industrial dyes, coumarin derivatives continue to be relegated to niche or small-scale formulations.

3. Conclusion

Coumarins, with their distinct photophysical properties, renewable origins, and chemical versatility, have firmly established themselves as valuable molecular platforms at the interface of natural product chemistry and applied chemical engineering. Their broad spectrum of structural modifiability and functional applications—ranging from optoelectronic devices and smart coatings to antimicrobial agents and eco-friendly polymers—positions them as indispensable tools in the advancement of sustainable technologies. Through both classical and modern synthetic methodologies, coumarin derivatives have been tailored to meet the demands of various industrial sectors, including pharmaceuticals, materials science, environmental engineering, and green energy. Despite the progress, several challenges remain to be addressed before coumarins can reach their full commercial and technological potential. These include limitations in sustainable large-scale synthesis, restricted availability of structurally diverse analogs, scalability of eco-friendly production methods, and unresolved issues of bioavailability and market integration. Nevertheless, the integration of coumarin-based systems into novel nanomaterials, functional composites, and biopolymeric matrices represents a significant leap forward in material innovation. Furthermore, advances in biocatalysis, flow chemistry, and artificial intelligence-assisted molecular design are expected to transform the way coumarins are synthesized and applied.

Looking ahead, interdisciplinary collaboration will be crucial to fully harnessing coumarins' potential. Future research should focus on refining green synthetic routes, exploring coumarin-based multifunctional architectures, and overcoming economic and regulatory barriers to commercial adoption. As the global shift toward circular and sustainable manufacturing continues, coumarins stand out as promising candidates to lead this transformation, merging the strengths of natural product chemistry with the precision of applied chemical engineering.

Conflict of interest

The authors declare no conflict of interest.

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