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Posted Date: 2 January 2026

doi: 10.20944/preprints202601.0092.v1

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Molecular Insights into the Management of Eugenol's Anticancer Action Against Colon Cancer: A Detailed Review

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Abstract

Colon cancer represents one of the most prevalent malignancies globally, influenced by genetic mutations, environmental factors, and chronic inflammatory processes. Natural phytochemicals, particularly eugenol derived from Syzygium aromaticum (cloves), demonstrate selective cytotoxicity toward malignant cells while preserving healthy cellular integrity. This review synthesizes current evidence on eugenol's physicochemical properties, absorption kinetics, and molecular mechanisms underlying its anticancer efficacy in colorectal carcinomas. Eugenol's multitargeted action encompasses apoptosis induction, cell cycle arrest, suppression of inflammatory pathways, and inhibition of metastatic progression. Furthermore, nanotechnological encapsulation strategies have been explored to enhance bioavailability and pharmacokinetic stability. The present analysis consolidates preclinical findings, discusses clinical translation challenges, and identifies future research directions for eugenol as an adjunctive therapeutic agent in cancer management.

Keywords: eugenol; colon cancer; apoptosis; phenolic compounds; anticancer mechanisms; natural products

1. Introduction

Colorectal cancer remains the second leading cause of cancer-related mortality globally, accounting for approximately 655,000 deaths annually [1,14–18]. Despite significant advances in surgical oncology, chemotherapy, and radiation therapy, treatment outcomes remain suboptimal, particularly in advanced stages, with many patients experiencing chemoresistance and severe adverse effects [2,19–21]. The search for novel therapeutic agents from natural sources has gained momentum due to their lower toxicity profiles and potential synergistic interactions with conventional anticancer drugs.

Eugenol (1-allyl-4-hydroxy-3-methoxybenzene), a simple phenolic compound extensively studied in recent years, demonstrates remarkable potential in cancer management [3,22–25]. This compound has a long historical precedent in traditional Ayurvedic and aromatherapeutic practices for managing diverse health conditions [4,26–31]. Beyond its medicinal applications, eugenol finds widespread utilization in dentistry, agriculture, and the flavor and fragrance industries due to its multifunctional properties [5,32–37].

The primary objective of this review is to provide a critical and comprehensive evaluation of eugenol's anticancer properties, with particular emphasis on its molecular targets in colon cancer pathogenesis. This analysis consolidates current scientific knowledge regarding eugenol's mechanisms of action, identifies pivotal signaling cascades involved in its anticancer effects, and examines its potential as an adjunctive or standalone therapeutic agent in colorectal cancer treatment.

 doi:10.20944/preprints202601.0092.v1

2. Physicochemical Properties of Eugenol

2.1. Chemical Structure and Molecular Characteristics

Eugenol ($C_{10}H_{12}O_2$) is a naturally occurring phenylpropanoid compound classified as a simple phenolic compound [6]. Its structure comprises three key functional groups: a phenolic hydroxyl group (-OH), a methoxy substituent ($-OCH_3$), and an allyl group ($-CH_2-CH=CH_2$) attached to an aromatic benzene ring. This arrangement is designated chemically as 2-methoxy-4-2-propenyl phenol [7].

The compound was first isolated in 1929 from clove oil derived from Eugenia caryophyllata [2]. Commercial production in the United States commenced in 1940, initially targeting the fragrance, flavoring, and dental industries due to its inherent antimicrobial and antiseptic properties [2].

2.2. Physical Properties

Eugenol exists as a clear to pale yellow liquid with a characteristic spicy, clove-like aroma [2]. Key physical characteristics include:

- Molar mass: 164.20 g/mol
- Density: 1.06 g/cm³
- Boiling point: 254°C
- pKa: 10.19
- Solubility: Sparingly soluble in water; readily soluble in organic solvents (ethanol, acetone, dimethyl sulfoxide)
- Physical state: Oily, viscous liquid

2.3. Chemical Stability and Reactivity

Eugenol exhibits chemical instability under certain environmental conditions[2]. The compound is susceptible to oxidation when exposed to light, atmospheric oxygen, and elevated temperatures[2]. Additionally, it undergoes chemical reactions with other compounds, potentially reducing its pharmacological efficacy and shelf stability. These inherent limitations have prompted researchers to investigate protective encapsulation strategies to maintain compound integrity in pharmaceutical formulations.

2.4. Natural Sources and Extraction

The richest natural source of eugenol is clove oil (Syzygium aromaticum), where eugenol constitutes 80-90% of the essential oil, with concentrations ranging from 9,381.7 mg to 14,650 mg per 100 g of fresh plant material[2][3]. Alternative botanical sources include:

- Cinnamon (Cinnamomum verum)
- Bay leaves (Laurus nobilis)
- Nutmeg (Myristica fragrans)
- Basil (Ocimum species)
- Flos magnolia

Industrial extraction typically employs steam distillation techniques yielding high-purity eugenol suitable for pharmaceutical and research applications.

3. Absorption, Metabolism, and Pharmacokinetics

3.1. Gastrointestinal Absorption

Following oral administration, eugenol undergoes rapid absorption across the gastrointestinal epithelium, entering the systemic circulation within 30-60 minutes[3]. The swift absorption profile, while ensuring bioavailability, paradoxically limits its therapeutic effectiveness at target tissues.

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Rapid intestinal transit reduces the window for localized colon-specific action, necessitating strategies to prolong residence time.

3.2. Hepatic Metabolism

Once systemic absorption occurs, eugenol is predominantly metabolized by hepatic cytochrome P450 enzymes, particularly CYP2A6 and CYP3A4, transforming the parent compound into various metabolites[3]. This hepatic first-pass metabolism results in rapid elimination, with over 90% being excreted within 24 hours as inactive conjugates, primarily sulfate and glucuronic acid derivatives[3]. This rapid clearance substantially limits eugenol's local bioavailability at colorectal tissues.

4. Enhancement of Bioavailability Through Encapsulation

4.1. Rationale for Encapsulation

Given eugenol's low aqueous solubility, chemical instability, and rapid metabolism, encapsulation within protective carriers has emerged as a pragmatic approach to optimize therapeutic efficacy[4]. Encapsulation techniques employ diverse delivery systems, including:

- Liposomal formulations
- Polymeric nanoparticles
- Solid lipid nanoparticles (SLN)
- Nanocochleates
- Nanoemulsions

4.2. Benefits of Encapsulation

Table 1. Benefits of Eugenol Encapsulation in Nanoformulations.

Benefit	Mechanistic Outcome
Sustained Release	Delays rapid absorption; prolongs colon residence time; extends therapeutic window
Enhanced Solubility	Improves aqueous dispersibility via hydrophilic carrier matrices; increases bioavailability
Oxidation Protection	Encapsulating material shields eugenol from light, heat, and atmospheric oxygen
Targeted Delivery	Carrier ligands enable selective colon or tumor-specific accumulation
Improved Bioactivity	Enhanced stability and solubility translate to superior therapeutic outcomes

5. Antioxidant Mechanisms

5.1. Free Radical Scavenging

Eugenol's antioxidant properties derive from its phenolic structural architecture, particularly the hydroxyl group attached to the aromatic ring[3]. This hydroxyl moiety facilitates hydrogen atom donation, enabling the compound to neutralize reactive free radicals, including phenoxy radicals, lipid peroxyl radicals, and other reactive oxygen species (ROS)[3].

5.2. Reactive Oxygen and Nitrogen Species Suppression

Beyond direct radical scavenging, eugenol inhibits the endogenous production of reactive oxygen species (ROS) and reactive nitrogen species (RNS) generated during cellular metabolism[3]. By reducing ROS/RNS generation, eugenol prevents oxidative damage to critical cellular macromolecules, including DNA, proteins, and membrane lipids[3].

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5.3. Enhancement of Endogenous Antioxidant Defenses

Eugenol augments the body's intrinsic antioxidant defense mechanisms, elevating expression of cytoprotective enzymes such as superoxide dismutase (SOD), catalase (CAT), and glutathione S-transferases (GSTs)[3]. This enhancement of endogenous defenses contributes to sustained cellular protection against oxidative stress.

5.4. Neuroprotection and Anti-Inflammatory Effects

Through monoamine oxidase (MAO) inhibition, eugenol modulates neurotransmitter homeostasis in the central nervous system, offering neuroprotective benefits[4]. Additionally, its anti-inflammatory properties suppress neuroinflammatory cascades, further supporting neuronal preservation.

5.5. Prevention of Mutagenic Events

By eliminating reactive molecular species and preventing accumulation of damaged DNA and proteins, eugenol reduces the likelihood of mutations that could precipitate malignant transformation and cancer development[3].

5.6. Repair of Oxidative Damage

Eugenol facilitates removal of oxidatively damaged macromolecules and supports regenerative processes, maintaining optimal cellular function and preventing long-term genomic injury[3].

6. Anticancer Mechanisms in Colon Cancer

6.1. Apoptosis Induction

Apoptosis, or programmed cell death, represents a primary mechanism through which eugenol exerts anticancer effects in colorectal carcinomas[5][6]. Multiple investigations have demonstrated eugenol's capacity to induce apoptosis in diverse colon cancer cell lines, including HT-29, HCT-116, Caco-2, and SW-620[5][6].

6.1.1. Reactive Oxygen Species-Mediated Apoptosis

In human promyelocytic leukemia cells (HL-60) and colorectal cancer models, eugenol triggers elevated intracellular ROS accumulation[5]. ROS overproduction overwhelms cellular antioxidant defenses, initiating the intrinsic apoptotic pathway. This pro-oxidant activity in cancer cells contrasts sharply with eugenol's cytoprotective antioxidant effects in normal cells, illustrating its selective anticancer action[5].

6.1.2. Mitochondrial Dysfunction and Membrane Depolarization

Eugenol-induced ROS elevation precipitates disruption of the mitochondrial membrane potential ($\Delta\Psi m$), a hallmark of intrinsic apoptosis[5][6]. Loss of mitochondrial membrane integrity triggers cytochrome c release into the cytosol, activating the caspase-9/caspase-3 cascade and culminating in programmed cell death[5][6].

6.1.3. Caspase Activation and p53 Upregulation

Eugenol enhances expression of the tumor suppressor protein p53, which transactivates pro-apoptotic genes (BAX, BAD, APAF-1) while suppressing anti-apoptotic genes (BCL-2, BCL-XL)[5]. Simultaneously, eugenol activates executioner caspases-3 and -7, facilitating cleavage of critical substrates (PARP, DFF45) and morphological manifestations of apoptosis[5][6].

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6.1.4. Cell Cycle Dynamics and Protein Expression Changes

Eugenol-treated cancer cells exhibit accumulation at the G2/M phase transition, accompanied by downregulation of cell cycle-promoting proteins (cyclin D1, cyclin B1, CDK2, CDK4) and upregulation of CDK inhibitors (p21, p27)[5][6]. The compound reduces expression of proliferating cell nuclear antigen (PCNA), reflecting suppressed DNA synthesis[5].

6.2. Anti-inflammatory Pathways

Chronic inflammation represents a critical cofactor in colorectal carcinogenesis[1][3]. Eugenol suppresses multiple inflammatory signaling cascades:

6.2.1. NF-κB Pathway Inhibition

The nuclear factor-κB (NF-κB) signaling pathway, constitutively active in many colorectal cancers, promotes expression of pro-survival and pro-inflammatory genes[3]. Eugenol inhibits IκB-α phosphorylation, preventing NF-κB nuclear translocation and transcriptional activity[3]. This translates to reduced production of inflammatory cytokines (TNF-α, IL-6, IL-8) and adhesion molecules facilitating tumor progression[3].

6.2.2. COX-2 and Prostaglandin Suppression

Cyclooxygenase-2 (COX-2) overexpression characterizes many colorectal malignancies, promoting prostaglandin E2 (PGE2) synthesis[3]. Eugenol downregulates COX-2 expression, reducing pro-tumorigenic prostaglandin production and associated inflammation[3].

6.2.3. MAPK Pathway Modulation

Eugenol modulates mitogen-activated protein kinase (MAPK) signaling, including ERK1/2, p38, and JNK pathways, which are frequently hyperactivated in colorectal cancers[3]. Suppression of MAPK cascade reduces cancer cell proliferation and survival[3].

6.3. Inhibition of Metastasis and Invasion

6.3.1. PI3K/Akt/mTOR Pathway Blockade

The phosphatidylinositol 3-kinase (PI3K)/protein kinase B (Akt) pathway represents a critical regulator of cell survival, proliferation, and invasion in colorectal cancers[5]. Eugenol blocks this pathway by reducing PI3K and Akt phosphorylation, suppressing downstream effectors (mTOR, GSK-3β) that promote tumor progression and metastatic dissemination[5].

6.3.2. Matrix Metalloproteinase Suppression

Matrix metalloproteinases (MMPs), particularly MMP-2 and MMP-9, facilitate extracellular matrix degradation enabling cancer cell migration and invasion[5]. Eugenol suppresses MMP expression and activity, reducing tumor cell invasive capacity[5].

6.3.3. Epithelial-Mesenchymal Transition (EMT) Inhibition

Eugenol suppresses EMT-promoting transcription factors (Snail, Slug, ZEB1), maintaining E-cadherin expression and cellular adhesion[5]. This attenuates acquisition of migratory phenotypes and metastatic competence[5].

6.4. Selective Cytotoxicity: Cancer vs. Normal Cells

A distinguishing feature of eugenol's anticancer action is its selective toxicity toward malignant cells while sparing normal tissue[5]. In comparative studies employing NCM-460 normal epithelial colon cells alongside Caco-2 and SW-620 cancer lines, eugenol (at concentrations of 300-800 μM)

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induced robust cell death in malignant populations without significantly impairing normal cellular viability[5]. This selectivity arises from differential expression of apoptotic machinery components and metabolic vulnerabilities in cancer cells[5].

7. Molecular Targets and Signaling Cascades

Table 2. Eugenol's Molecular Targets in Colon Cancer Cells.

Pathway/Protein	Effect of Eugenol	Consequence
ROS Production	↑ Elevation	Apoptosis induction
Mitochondrial ΔΨm	↓ Depolarization	Intrinsic apoptosis activation
Caspase-3/9	↑ Activation	Programmed cell death execution
p53	↑ Upregulation	Pro-apoptotic gene transactivation
Bcl-2/Bcl-XL	↓ Downregulation	Reduced anti-apoptotic signaling
Bax/Bad/Bid	↑ Upregulation	Enhanced apoptotic signaling
Cyclin D1/B1	↓ Reduction	G2/M cell cycle arrest
PCNA	↓ Suppression	Reduced DNA synthesis
NF-κB	↓ Inhibition	Diminished pro-tumorigenic transcription
COX-2	↓ Downregulation	Reduced pro-inflammatory signaling
PI3K/Akt	↓ Inhibition	Suppressed survival and invasion
MMP-2/9	↓ Suppression	Reduced metastatic capacity
E-cadherin	↑ Maintenance	Preserved cellular adhesion

8. Genetic Basis of Colon Cancer Susceptibility

8.1. Hereditary Colon Cancer Syndromes

8.1.1. Familial Adenomatous Polyposis (FAP)

Mutations in the adenomatous polyposis coli (APC) gene predispose individuals to FAP, characterized by development of hundreds to thousands of colonic polyps by the third decade of life[1]. Without intervention, colorectal cancer inevitably develops by age 40[1]. The APC protein functions as a negative regulator of Wnt/β-catenin signaling; loss-of-function mutations lead to constitutive pathway activation and uncontrolled cell proliferation[1].

8.1.2. Lynch Syndrome (Hereditary Nonpolyposis Colorectal Cancer)

Lynch syndrome arises from germline mutations in DNA mismatch repair (MMR) genes: MLH1, MSH2, MSH6, and PMS2[1]. These genes encode proteins responsible for detecting and correcting DNA replication errors. Defective MMR leads to microsatellite instability (MSI) and accumulation of mutations throughout the genome, dramatically increasing colorectal cancer risk[1]. Lynch syndrome patients typically develop cancer at younger ages (40-50 years) compared to sporadic colorectal cancer[1].

8.2. Somatic Mutations in Colorectal Cancers

Beyond inherited syndromes, colorectal cancers accumulate somatic mutations in oncogenes (KRAS, MYC) and tumor suppressors (TP53, PIK3CA, BRAF)[1]. KRAS mutations promote constitutive growth signaling via Ras/RAF/MEK/ERK cascade activation[1]. TP53 mutations eliminate p53-mediated apoptosis and cell cycle checkpoints[1].

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9. Environmental and Lifestyle Risk Factors

9.1. Dietary Influences

9.1.1. Red and Processed Meat Consumption

High consumption of red meat (beef, lamb, pork) and processed meat products (bacon, sausages, hot dogs) significantly elevates colorectal cancer risk[1][3]. Carcinogenic compounds generated during processing (N-nitroso compounds) and high-temperature cooking (heterocyclic amines) directly damage colonic DNA[1][3].

9.1.2. Protective Dietary Factors

Conversely, diets rich in fiber, fruits, vegetables, whole grains, calcium, and vitamin D exhibit protective effects[1]. Dietary fiber binds potential carcinogens, reducing local concentration and toxic exposure. Antioxidants and phytochemicals from plant sources neutralize reactive species and modulate inflammatory pathways[1].

9.2. Physical Activity and Weight Management

Sedentary behavior associates with increased colorectal cancer incidence; conversely, regular moderate-to-vigorous physical activity reduces risk by improving immune function, promoting healthy adiposity, and reducing systemic inflammation[1][3].

9.3. Tobacco and Alcohol Use

Both cigarette smoking and excessive alcohol consumption elevate colorectal cancer risk through multiple mechanisms including direct DNA damage, inflammation promotion, and altered carcinogen metabolism[1][3].

10. Safety Profile and Toxicological Considerations

10.1. Regulatory Status and Safe Use

Eugenol has been classified as "Generally Recognized as Safe" (GRAS) by the U.S. Food and Drug Administration (FDA) for use as a food additive[4]. The World Health Organization (WHO) and Food and Agriculture Organization (FAO) have established an acceptable daily intake (ADI) of 2.5 mg/kg body weight[4]. At therapeutic concentrations, eugenol demonstrates excellent safety profiles, being widely incorporated into foods, cosmetics, dental products, and traditional medicines[4].

10.2. Toxicity at High Concentrations

However, eugenol exhibits dose-dependent toxicity when ingested at high concentrations, particularly undiluted clove oil[4]. As little as 5-10 mL of concentrated clove oil can precipitate severe toxicity, especially in pediatric populations[4]. High-dose exposure may cause acute hepatic and renal failure, CNS depression, seizures, and anaphylaxis-like hypersensitivity reactions[4].

10.3. Genotoxicity and Carcinogenicity

Research on eugenol's genotoxic potential has yielded conflicting results; some studies indicate potential for genetic damage, while others demonstrate protective antigenotoxic effects[4]. However, major regulatory bodies including the International Agency for Research on Cancer (IARC) do not classify eugenol as a human carcinogen based on current evidence[4].

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10.4. Hypersensitivity and Irritant Potential

Eugenol can cause allergic contact dermatitis and mucosal irritation, particularly in susceptible individuals[4]. Rare hypersensitivity reactions, including anaphylaxis-like symptoms, have been documented in dental settings[4].

11. Synergistic Interactions with Conventional Chemotherapy

Emerging evidence suggests eugenol enhances anticancer efficacy of conventional chemotherapeutic agents[5][6]. Combination treatments employing eugenol with doxorubicin, gemcitabine, and other chemotherapy drugs demonstrate superior cell death compared to monotherapy[5][6]. This synergistic effect likely derives from eugenol's multitargeted mechanism complementing distinct pharmacological actions of chemotherapy agents.

12. Challenges and Future Research Directions

12.1. Translational Challenges

Despite promising preclinical data, significant obstacles impede clinical translation:

1. **Chemical Stability:** Eugenol's susceptibility to oxidation necessitates protective formulation strategies.
2. **Bioavailability Optimization:** Rapid hepatic metabolism and intestinal absorption limit local colonic concentration.
3. **Dose Standardization:** Varying extraction methods and plant source quality necessitate standardized pharmaceutical-grade preparations.
4. **Clinical Trial Design:** Well-designed phase I/II trials are required to establish safety and efficacy in human colorectal cancer patients.

12.2. Future Research Priorities

1. **Advanced Delivery Systems:** Development of colon-targeted nanoformulations enabling selective accumulation in malignant tissues.
2. **Omics-Based Mechanistic Studies:** Integration of transcriptomics, proteomics, and metabolomics to elucidate comprehensive molecular targets.
3. **Combination Therapy Optimization:** Systematic investigation of eugenol synergy with immunotherapies, targeted agents, and conventional chemotherapy.
4. **Biomarker Identification:** Discovery of predictive biomarkers identifying patient populations most likely to benefit from eugenol-based treatments.
5. **Pharmacogenomic Analysis:** Investigation of genetic polymorphisms affecting eugenol metabolism and therapeutic responsiveness.

13. Conclusion

Eugenol emerges as a multifunctional phytochemical demonstrating substantial promise in colorectal cancer management. Its mechanism of action encompasses diverse biological pathways—apoptosis induction, cell cycle arrest, inflammatory suppression, and metastasis inhibition—enabling comprehensive therapeutic impact against malignant cells while maintaining selective sparing of normal tissues. The compound's antioxidant properties protect against genotoxic damage in healthy cells while paradoxically facilitating pro-oxidant stress in cancer cells, representing a unique pharmacological advantage.

Nanotechnological encapsulation strategies offer viable approaches to overcome eugenol's inherent chemical limitations and optimize bioavailability. The substantial body of preclinical evidence, combined with eugenol's favorable safety profile and regulatory acceptance, positions it as a promising candidate for adjunctive or integrative cancer therapy. However, rigorous clinical

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investigation and optimization of delivery systems remain essential prerequisites for realizing its therapeutic potential in patients with colorectal malignancies.

The convergence of traditional botanical knowledge and contemporary molecular pharmacology exemplified by eugenol research demonstrates the continuing relevance of natural products in modern therapeutic development. Future investigations should prioritize translational research integrating advanced omics technologies, targeted nanoformulations, and carefully designed clinical trials to establish eugenol's definitive role in colorectal cancer prevention and treatment strategies.

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