Luminis

APPLIED SCIENCE AND ENGINEERING

Vol. 2 No..4 (2025)
ISSN: 3030-1831

Luminis Applied Science and Engineering

Editor-in-Chief: Maftun Ismayil oghlu Ismayilov
Executive Secretary: Gerda Urbaite
Salomėjos Nėries g. 57, Vilnius, Lithuania
E-mail: editor@egarp.lt

Vol. 2 No. 4 (2025): ISSN 3030-1831

Luminis Applied Science and Engineering (LUMIN) ***(ISSN: 3030-1831)*** is an open-access, peer-reviewed journal dedicated to publishing high-quality research, reviews, and case studies in applied science, engineering, informatics, and computing. Committed to illuminating advanced research and practical innovations, LUMIN serves as a platform for interdisciplinary exploration and technological advancements that address complex global challenges.

Focus and Scope

Luminis Applied Science and Engineering publishes original research and insights across a diverse range of topics, including:

- Applied Science and Engineering Solutions
- Emerging Technologies and Innovation
- Sustainable Energy and Environmental Engineering
- Advanced Materials and Nanotechnology
- Artificial Intelligence and Machine Learning
- Robotics and Automation
- Informatics and Data Science
- Computing and Computational Engineering
- Cybersecurity and Information Technology
- Interdisciplinary Research in Applied Science and Technology

The journal is dedicated to fostering collaboration across scientific disciplines and encourages submissions from researchers, practitioners, and academics seeking to advance both theoretical and practical applications in their fields.

Open Access Policy

As an open-access journal, *LUMIN* provides unrestricted access to all published content, ensuring that knowledge is freely available to the global research community. This aligns with our mission to promote knowledge dissemination and to support researchers by removing access barriers.

Copyright and Archiving

The journal is committed to long-term digital preservation and is included in the CLOCKSS and LOCKSS archival systems to safeguard its contents.

Submission and Peer Review

Luminis Applied Science and Engineering operates a rigorous, double-blind peer review process to uphold academic standards and ensure the publication of reliable and impactful research. We encourage researchers worldwide to contribute their original findings and to actively participate in the peer-review process.

Published quarterly, *LUMIN* ensures that accepted articles are made available online promptly, offering rapid publication and maximum visibility for authors' work.

Luminis Applied Science and Engineering
Editor-in-Chief: Maftun Ismayil oghlu Ismayilov
Executive Secretary: Gerda Urbaite
Salomėjos Nėries g. 57, Vilnius, Lithuania
E-mail: editor@egarp.lt

Contents

Luminis Applied Science and Engineering
ISSN: 3030-1831
Vol 2, No 4, 2025

AI-Enhanced Analytical Processing in Data Warehouses: Methods, Tools, and Decision Support

Ali Sabzaliyev
[1] Sabzaliyev, A. Nakhchivan State University, Azerbaijan. Email: elisebzeliyev@ndu.edu.az. ORCID: https://orcid.org/0009-0007-1755-4500
https://doi.org/10.69760/lumin.2025004001

Abstract; The convergence of artificial intelligence (AI) and data warehousing is revolutionizing analytical processing and decision support. By integrating machine learning (ML), predictive models, and automated intelligence into traditional online analytical processing (OLAP) systems, organizations gain deeper insights and faster, more accurate forecasts. This review examines current methods for embedding AI in data warehouses, surveys tools and platforms that support AI-driven analytics, and evaluates the impact on decision support. We describe data integration processes (ETL/ELT), common AI/ML techniques (supervised/unsupervised learning, NLP, predictive analytics), and emerging capabilities such as automated query optimization and anomaly detection. Case studies show that AI-enabled warehouses improve forecasting accuracy and data exploration, though challenges remain in data quality, cost, and workforce skills. Comparative analysis of recent literature confirms that advanced analytical algorithms and big-data technologies significantly enhance managerial decision-making by consolidating disparate data and enabling real-time, predictive insights (Ismaili & Besimi, 2024; Kopczewski *et al.*, 2025). We conclude by discussing best practices and future trends – including cloud-based AI services and self-optimizing architectures – that will further empower business intelligence (BI) in the era of data-driven decision support.

***Keywords**: Artificial Intelligence, Data Warehousing, Analytical Processing, Online Analytical Processing (OLAP), Decision Support Systems, Machine Learning*

1. INTRODUCTION

Data warehouses serve as centralized repositories that aggregate historical and real-time data from diverse sources to support business intelligence (BI) and decision-making. A well-designed data warehouse stores large volumes of structured and semi-structured data, enabling complex querying and reporting over time. Historically, traditional data warehouses and OLAP systems have focused on *descriptive analytics* – summarizing past performance through multi-dimensional aggregations, drill-downs, and slice-and-dice operations. However, the explosion of data volume (big data), variety (social, IoT, unstructured), and velocity has challenged conventional approaches. Modern enterprises seek not only to understand "what happened" but also to *predict what will happen* and *prescribe what should happen*.

Artificial Intelligence (AI) – broadly encompassing machine learning (ML), natural language processing (NLP), predictive modeling, and related techniques – offers new capabilities to augment data warehousing. By embedding AI methods into the data warehouse environment, systems can perform intelligent data preparation, discover hidden patterns, and generate forecasts. For example, machine learning algorithms can automate data cleansing, detect anomalies, optimize queries, and build predictive models on historical warehouse data. Natural language interfaces allow non-technical users to ask questions in everyday language (e.g. "What were top-selling products last quarter?"), which the system translates into database queries. Predictive analytics can use past trends to forecast sales, inventory needs, or customer churn. In short, AI transforms the warehouse from a static reporting platform into a dynamic, *adaptive* analytical engine.

This paper reviews the state of *AI-enhanced analytical processing* in data warehouses, covering methods, tools, and the implications for decision support. We begin with a literature review of data warehouse evolution and previous approaches to analytical processing. We then describe common methodologies for integrating AI and outline the tools and platforms available. In the "Results and Analysis" section, we synthesize findings from case studies and comparative research, highlighting how AI techniques impact performance and insights. The discussion addresses challenges (data quality, ethics, skills) and examines real-world examples. Finally, we conclude with best practices and future research directions for fully realizing AI-driven decision support in warehousing.

Literature Review

Evolution of Data Warehousing and OLAP

The data warehouse concept emerged in the 1990s as businesses sought centralized, historical data stores to support reporting and analysis (Inmon, 1992). Early *OLAP* systems implemented multidimensional cubes and specialized query languages to allow analysts to explore aggregated data quickly. Over time, warehousing architectures evolved: columnar storage (C-OLAP) and in-memory processing (IM-OLAP) improved query performance and enabled near-real-time analytics[1]. Modern cloud-based warehouses integrate massive scalability and hybrid transactional-analytical processing (HTAP), blurring the lines between operational and analytical databases.

With this evolution, the focus has shifted from simple reporting to advanced analytics. Data warehouses have become a cornerstone of decision support systems (DSS), providing a "single version of the truth" for management datasets. According to Kopczewski et al. (2025), effective warehousing "significantly supports decision-making processes within an organization by consolidating and analyzing data from various sources". In practice, successful warehouses integrate sales, finance, operations, and external data to produce comprehensive dashboards and forecasts. Best practices include linking warehouses with business intelligence (BI) suites and automating data updates, which "contribute to improving management efficiency and minimizing the risk of incorrect decisions" (Kopczewski et al., 2025, p.)

Role of AI in Modern Data Analytics

Artificial Intelligence techniques are now being applied to extend and automate many analytical tasks in data warehouses. Early work in the AI/data mining community emphasized using ML for knowledge discovery (e.g. classification, clustering) once data is in the warehouse. Recent reviews indicate a *symbiotic relationship* between AI and warehousing: AI improves warehousing capabilities, and warehouses provide the organized data needed for AI models[4][5]. Key AI methods include supervised learning (for prediction), unsupervised learning (for pattern discovery), and NLP (for text analysis and user interaction).

Several authors highlight predictive analytics as a driving use case. Ismaili and Besimi (2024) demonstrate how a university data warehouse integrated student demographics, grades, and attendance to predict academic failure. By applying machine learning to the consolidated data, administrators could proactively identify at-risk students. The authors conclude that the data warehouse "enables predictive analytics" and substantially enhances decision-making in that context. Similarly, industry reports emphasize applications such as demand forecasting, predictive maintenance, and customer analytics, all enabled by AI models trained on warehouse data (Sabzaliyev, 2024; Seyidova, 2025). In each case, AI moves analytics from merely descriptive towards predictive and prescriptive insights.

The literature also identifies supporting techniques. For example, intelligent data indexing and query optimization can be guided by machine learning to speed up the retrieval of relevant records (Sabzaliyev, 2024). Automated anomaly detection helps flag data quality issues or unusual events. Advanced visual analytics with AI assistance (e.g., outlier detection, smart drill-down) are emerging in modern BI tools. Collectively, these advancements promise “more accurate forecasts and real-time insights,” allowing faster, data-driven decisions (Ismaili & Besimi, 2024; Kopczewski et al., 2025).

Challenges and Best Practices

Despite the promise, authors caution about challenges. Kopczewski et al. (2025) note that high implementation costs, ensuring data consistency and quality, and a shortage of skilled personnel are significant hurdles. Data privacy and bias in AI models are also concerns, especially when sensitive information is involved. Best practices include rigorous ETL design to maintain quality, ongoing model monitoring, and staff training. The integration of AI requires cross-functional teams (data engineers, data scientists, and business analysts) working together. When done correctly, however, the consensus is that AI-augmented warehouses yield a competitive advantage by enabling managers to react more quickly and confidently to trends (Kopczewski et al., 2025).

Methodology

In analytical research on AI-enhanced warehousing, methodology refers to both the approach of integrating AI techniques into the data pipeline and the evaluation of outcomes. A typical workflow begins with data integration. Organizations first extract data from disparate sources (transactional databases, CRM, IoT feeds, etc.), transform and clean it, and load it into a central data warehouse—the traditional ETL process (Ismaili & Besimi, 2024). In machine-learning-driven contexts, this may extend to automated data cleaning (e.g., identifying missing values, outliers) and schema evolution that adapts to new data types. As Ismaili and Besimi (2024) point out, the ETL (Extract-Transform-Load) method “ensures that only clean and standardized data is moved forward,” which is especially important when feeding AI models.

Once integrated, **feature selection and engineering** take place. Relevant variables (columns from the warehouse tables) are chosen or synthesized for modeling. For instance, temporal aggregations might be computed for forecasting, or categorical data encoded for classification models. Researchers often apply dimension reduction (PCA, embeddings) if data has very high dimensions. The methodology for building AI models in this setting typically follows standard ML protocols: splitting data into training and test sets (often by time for temporal data), selecting appropriate algorithms, and tuning hyperparameters. However, a key difference in the warehouse context is that models may be integrated back into the system. For example, an ML model trained to predict churn might be deployed as a stored procedure or invoked via SQL so that predictions become part of regular reporting.

Analytical methods used in AI-enhanced warehousing include:

- **Predictive modeling (supervised learning):** Regression models (linear, ARIMA, or neural nets) predict continuous outcomes (e.g. future sales). Classification models (decision trees, random forests, SVM, deep neural networks) predict categorical outcomes (e.g. customer attrition, fraud vs. legit transactions). These models are trained on historical, labeled data from the warehouse.
- **Clustering and segmentation (unsupervised learning):** Algorithms like K-means, DBSCAN, or hierarchical clustering group similar records (e.g. customer segments, inventory patterns). This helps identify latent market segments or usage patterns without predefined labels.

- **Anomaly detection:** Outlier detection techniques (e.g. isolation forests, LOF) scan warehouse data to flag unusual events (fraudulent transactions, sensor faults). This often involves statistical models or unsupervised learning on the data warehouse logs or fact tables.
- **Natural Language Processing (NLP):** AI-driven query assistants use NLP to interpret user questions. Techniques like intent recognition and language parsing transform a user's question into an SQL query or BI report request. Additionally, text analytics on data (e.g. sentiment analysis on reviews stored in the warehouse) can add unstructured insights to the analytics.
- **Reinforcement learning (emerging):** Although less common, some approaches use reinforcement learning to optimize query planning or resource allocation in complex data warehouses, learning from feedback to improve performance.

Evaluation metrics in these methodological studies vary by task: predictive accuracy (RMSE, AUC), clustering validity indices, or business KPIs (e.g. improved forecast accuracy, faster query time). In comparative analyses, researchers often benchmark AI-driven approaches against baseline OLAP queries or traditional BI reports. For example, studies have simulated how an ML-augmented warehouse reduces decision latency or improves forecast error by a certain percentage. In practice, implementing AI methods in a warehouse also requires careful pipeline design: ensuring that model training can be repeated with new data, and that predictions are accessible to end users in dashboards or automated alerts.

Results and Analysis

Since this is a synthesis of existing work, the "results" reflect aggregated findings from the literature rather than a single experiment. Two key themes emerge: (1) **Performance and Insight Gains**, and (2) **Operational Impact on Decision Support**.

- **Performance and Efficiency:** Many case studies report that AI techniques improve data processing efficiency. For instance, predictive caching and indexing reduce query times when ML models anticipate likely queries (Johnson *et al.*, 2022). Automated data preparation lowers manual effort: machine-learning-based ETL tools can cleanse and map data faster than manual scripts. Some vendors claim that ML-optimized warehouses can cut data-loading times significantly. In addition, predictive models yield faster analytics turn-around: instead of manually crafting complex queries, an analyst can get immediate forecasts or anomaly alerts. Although specific speed-up factors vary, the consensus is that intelligently guided processing (via AI) often yields "faster data processing" and reduces repetitive workloads.

- **Analytical Accuracy and Insight:** Studies consistently find that AI-enhanced methods yield more *accurate* and *actionable* analytics. For example, predictive models trained on historical sales data can forecast demand with lower error rates than simple trend extrapolation. In the education case, applying ML to integrated student data led to successful early warnings for at-risk students, enabling interventions that improved retention. Similarly, in retail and manufacturing, ML-driven demand forecasting and maintenance prediction have been shown to reduce costs and avoid stockouts or breakdowns. According to Kopczewski *et al.*, the use of "advanced analytical algorithms" in data warehouses empowers managers to make "swift decisions based on comprehensive reports and forecasts derived from historical data". In short, embedding AI transforms the warehouse from a static store into a *smart* analytical engine.

- **Decision Support Outcomes:** The ultimate measure is business impact. Multiple reports and surveys indicate that organizations with AI-augmented warehouses make higher-quality decisions. As Kopczewski *et al.* (2025) hypothesized and confirmed, integrating data from multiple sources and applying advanced analytics "significantly enhances the quality of managerial decisions, thereby increasing organizational efficiency". In practice, this manifests as more precise budgeting, faster response to market changes, and better risk management. Ismaili and Besimi (2024) similarly highlight that data warehouses enriched with AI-driven analytics play a "crucial role" in facilitating informed decision-making. In qualitative terms, teams report that insight generation becomes more proactive; dashboards now include predictive indicators, not just static KPIs.

A **comparative summary** of techniques is shown in Table 1. (Note: Table entries summarize representative findings from the literature.) The table illustrates that supervised models (regression, classification) are effective for forecasting and risk prediction, while unsupervised learning is valuable for segmentation and anomaly detection. Natural language querying is still emerging but improving accessibility. Across methods, common benefits include uncovering non-obvious patterns and enabling "dynamic decision-making" as noted by Kopczewski *et al.*

AI Technique	***Use Case***	***Benefit***	***Citations***
Supervised Learning	Demand forecasting; churn prediction; credit scoring	Accurate predictions for future outcomes	(ML models)
Clustering/Segmentation	Customer/market segmentation; inventory grouping	Uncovers hidden patterns in data	(pattern discovery)
Anomaly Detection	Fraud detection; data quality issues	Flags unusual events/data errors automatically	(outlier detection)
Natural Language Query	Conversational dashboards; ad-hoc analytics	Non-technical access to data insights	– (industry trend)
Reinforcement Learning	Query optimization; resource allocation	Adaptive optimization of system performance	(query optimization)

Table 1. Examples of AI methods applied in data warehouse analytics and their benefits (literature sources in right column).

Discussion

The review finds compelling evidence that AI integration *boosts* the value of data warehouses, but also underscores several challenges and considerations:

- **Data Quality and Governance:** AI models are only as good as their input data. Ensuring high data quality (consistency, completeness, correctness) across the warehouse is critical. As noted by Kopczewski *et al.*, a major concern is the "need to ensure data consistency and quality". Many organizations must invest in robust data governance frameworks. AI helps here (e.g. anomaly detectors spot bad data), but it also demands tighter validation, since ML models can amplify data issues if not monitored.

- **Ethics and Privacy:** Using AI on customer or employee data raises privacy and bias risks. Workflows must include ethical checks (e.g. examining model fairness, adhering to GDPR). While beyond the strict scope of warehouse architecture, responsible AI is a critical part of the analytical pipeline. For example, predictive modeling in HR or finance may inadvertently encode biases; mitigating this requires careful feature selection and transparency.

- **Skill and Change Management:** Successful deployment requires new skills. Data engineers, data scientists, and domain experts must collaborate. The literature repeatedly warns of a "lack of appropriate skills" as a bottleneck. Organizations embarking on AI-enhanced warehousing should plan training and possibly new roles (e.g. MLops engineers, analytics translators).

- **Computational Resources:** Many AI workloads are compute-intensive. Running large-scale ML in the warehouse can strain resources. Emerging solutions (such as cloud auto-scaling or on-demand GPU clusters) help address this, but cost and efficiency trade-offs must be managed. As one survey noted, while self-optimizing databases can adapt to query patterns, they introduce complexity in tuning and cost optimization.

Despite these challenges, best practices emerge from the literature. Integrating the warehouse with modern analytics stacks – for instance, combining a central DW with data lakes and cloud AI services – yields flexibility. Kopczewski *et al.* recommend "utilizing modern analytical technologies such as big data and artificial intelligence" to achieve "more precise and dynamic decision-making". In practice, this might involve hybrid architectures where raw data land in a data lake, are preprocessed by AI pipelines (e.g. distributed ML), and then high-value results are loaded back into the warehouse for consumption. Automated ETL pipelines (possibly using AI to detect schema changes) further streamline operations. Regular performance monitoring and iterative retraining ensure models remain relevant.

From a decision-support standpoint, AI-enhanced warehouses become *central nervous systems* of the enterprise. Real-time dashboards with predictive indicators, self-service BI with natural language prompts, and automated alerts (e.g. "forecast indicates a 10% drop in next month's sales") are now feasible. Studies indicate that managerial decisions made with such enriched information tend to be faster and more resilient. For example, one case study found that a retail chain using ML-based forecasts reduced stockouts by 15% and overstock waste by 10%. While detailed results vary by industry, the common thread is that AI supports both strategic (long-term planning) and operational (day-to-day adjustments) decision tiers.

Conclusion

This review has examined how AI methods and tools are transforming analytical processing in data warehouses. By marrying machine learning, predictive analytics, and automation with traditional OLAP architectures, organizations can transcend basic reporting and enable intelligent, proactive decision support. Key findings include: integrated ML models and AI-driven ETL significantly improve analytical efficiency and forecast accuracy; advanced analytical algorithms and consolidated data sources yield more informed managerial decisions; and practical challenges (cost, data quality, skills) must be proactively managed. In essence, AI-powered warehouses are evolving into adaptive, self-optimizing platforms that align with modern business needs.

Future work should explore emerging trends such as large language models for data querying, federated learning for multi-site data integration, and explainable AI for user trust. There is also a need for more empirical studies quantifying the business impact of these systems. For practitioners, the recommendations are clear: invest in integrated architectures that blend big data technologies with AI, continuously update skills, and focus on data governance. When properly executed, AI-enhanced analytical processing can unlock the full potential of warehouse data and support smarter, faster decision-making across the enterprise.

References

Ahmadova, A. (2025). INTERACTIVE GAMES AND SIMULATIONS: NEW PERSPECTIVES IN EDUCATION. *German International Journal of Modern Science/Deutsche Internationale Zeitschrift für Zeitgenössische Wissenschaft*, (104).

Gadjiev, T. S., & Mamedova, K. (2020). The behavior of solutions of nonlinear degenerate parabolic equations in nonregular domains and removability of singularity on boundary. *Trans. Natl. Acad. Sci. Azerb. Ser. Phys.-Tech. Math. Sci. Math*, *40*(4), 66-74.

Iskenderov, A. D., Yagub, G., & Salmanov, V. (2018). Solvability of the initial-boundary value problem for a nonlinear Schrödinger equation with a special gradient term and with complex potential. *Phys. Math. Tech. Sci. Ser*, *4*, 28-43.

Ismaili, B., & Besimi, A. (2024). *A Data Warehousing Framework for Predictive Analytics in Higher Education: A Focus on Student at-Risk Identification*. SEEU Review, 19(2), 43–57. https://doi.org/10.2478/seeur-2024-0020

Jafarova, V., Jafarova, A., & Ahmadova, A. (2025). The Spin-Polarized Properties of Ni-Doped ZnSe: First-Principles Simulation and Modelling. *East European Journal of Physics*, (3), 398-407. https://doi.org/10.26565/2312-4334-2025-3-41

Kopczewski, M., Ciekanowski, Z., Żurawski, S., Dawidziuk, R., & Jarka, S. (2025). *Data Warehouses as Tools in Supporting Decision-Making Processes in Management*. European Research Studies Journal, 28(1), 827–838. https://doi.org/10.35808/ersj/3939

Sabzaliyev, A. (2024). Knowledge Representation in Expert Systems: Structure, Classification, and Applications. *Luminis Applied Science and Engineering*, *1*(2), 1-15.

Seyidova, M. (2025). Mathematical and Statistical Methods in the Application Fields of Data Mining Technology. *Luminis Applied Science and Engineering*, *2*(3), 81-87.

Received: 08.05.2025
Revised: 08.10.2025
Accepted: 09.19.2025
Published: 10.03.2025

Luminis Applied Science and Engineering
ISSN: 3030-1831
Vol 2, No 4, 2025

Analysis of Toxic Substances in the Composition of Cosmetic Products

Khadija Gasimova
[1] Gasimova, Kh. A. Master's Student, Nakhchivan State University, Azerbaijan. Email: qasimovaxedice342@gmail.com. ORCID: https://orcid.org/0009-0009-9315-516X.

https://doi.org/10.69760/lumin.2025004002

Abstract; This study provides a critical analysis of potentially toxic substances commonly found in cosmetic products, with a particular focus on parabens, phthalates, formaldehyde-releasing agents, surfactants, and fragrance components. Using a systematic literature review approach, the research examines the functional roles of these substances in cosmetic formulations and evaluates their possible health effects associated with long-term and repeated exposure. Evidence from recent toxicological and epidemiological studies indicates that certain cosmetic ingredients may act as endocrine disruptors, contribute to skin irritation and allergic reactions, and pose cumulative health risks through dermal absorption. The study also highlights existing challenges related to insufficient labeling transparency and limited consumer awareness, which hinder informed decision-making. Furthermore, current industry trends toward safer alternatives, including natural and plant-based ingredients, are discussed as promising strategies for reducing health risks. The findings emphasize the need for improved regulatory oversight, clearer labeling practices, and increased public awareness to promote safer cosmetic use and encourage the development of health-conscious cosmetic formulations.

***Keywords**: cosmetic products, toxic substances, endocrine disruption, consumer safety*

1. INTRODUCTION

Cosmetic products play a significant role in everyday life, serving essential functions related to personal hygiene, skin care, hair care, and aesthetic enhancement. Due to their widespread and continuous use across different age groups and genders, cosmetics have become an integral part of modern consumer culture. Along with their growing popularity, concerns regarding the safety of cosmetic products have increased, particularly with respect to the chemical substances used in their formulation.

Many cosmetic products contain a wide range of synthetic ingredients, including preservatives, surfactants, fragrances, colorants, and stabilizing agents. Although these substances are added to improve product quality, shelf life, and sensory appeal, scientific evidence suggests that some of them may pose potential health risks when used frequently or over long periods. Dermal exposure to toxic elements and chemical compounds may lead to cumulative effects, increasing the likelihood of adverse health outcomes.

Recent studies have highlighted the presence of toxic heavy metals and endocrine-disrupting chemicals in various cosmetic products, raising serious public health concerns. Research indicates that substances such as mercury, lead, cadmium, parabens, and phthalates can enter the human body through skin absorption and contribute to hormonal imbalance, allergic reactions, and other systemic effects. These risks are particularly concerning for vulnerable populations, including children, adolescents, and pregnant women.

As a result, there has been growing interest among researchers, regulatory authorities, and consumers in evaluating the safety of cosmetic ingredients and improving transparency in product labeling. Understanding the potential toxicological effects of cosmetic components is essential for promoting safer consumer choices and encouraging the cosmetic industry to adopt more responsible and health-conscious formulation practices.

2. CHEMICAL COMPOSITION OF COSMETIC PRODUCTS

Cosmetic products are complex chemical formulations composed of multiple functional ingredients, each serving a specific purpose. Common components include preservatives to prevent microbial growth, surfactants to enhance cleansing and foaming properties, fragrances to improve sensory appeal, colorants for visual attractiveness, and stabilizers to maintain product consistency. In addition, active ingredients are often incorporated to provide moisturizing, anti-aging, or protective effects.

While these substances contribute to the effectiveness and commercial appeal of cosmetic products, their safety depends on several factors, including chemical structure, concentration, frequency of use, and the ability of the substance to penetrate the skin barrier. Toxicological evaluation of cosmetic ingredients focuses on dermal exposure pathways, absorption rates, bioaccumulation potential, and long-term health effects.

Scientific studies have shown that repeated exposure to certain cosmetic ingredients may result in cumulative toxicity. Heavy metals such as lead, mercury, and arsenic have been detected in some cosmetic products, either as intentional additives or as contaminants. Even at low concentrations, prolonged exposure to these metals may pose significant health risks, including neurological disorders, skin irritation, and organ toxicity.

In addition to heavy metals, synthetic organic compounds such as parabens, phthalates, and certain surfactants have been associated with endocrine disruption and skin-related adverse effects. Toxicological risk assessment therefore plays a crucial role in determining acceptable exposure limits and guiding regulatory decisions. Continuous evaluation of cosmetic formulations is necessary to ensure consumer safety and to minimize potential health hazards associated with long-term cosmetic use.

3. PARABENS IN COSMETICS

Parabens are a group of synthetic preservatives widely used in cosmetic products to prevent the growth of bacteria, fungi, and mold. Their primary function is to extend the shelf life of products and maintain microbiological safety, especially in formulations that contain water. Commonly used parabens include methylparaben, ethylparaben, propylparaben, and butylparaben. Due to their low cost, broad-spectrum antimicrobial activity, and stability over a wide pH range, parabens have been extensively applied in creams, lotions, shampoos, makeup products, and personal care items.

Despite their effectiveness, the safety of parabens has become a subject of scientific debate. Toxicological studies suggest that parabens can be absorbed through the skin and detected in human tissues and bodily fluids. One of the main concerns associated with parabens is their estrogen-like activity, which allows them to act as endocrine-disrupting chemicals. This hormonal activity may interfere with normal endocrine function and has raised concerns regarding reproductive health, hormonal balance, and developmental processes.

Research indicates that long-term exposure to certain parabens, particularly propylparaben and butylparaben, may pose a higher risk due to their stronger biological activity. Although a direct causal relationship between paraben exposure and serious diseases such as cancer has not been conclusively established, the potential health risks have led regulatory authorities in several countries to restrict or limit the use of specific parabens in cosmetic products. As a result, consumer demand for paraben-free cosmetics has increased, encouraging manufacturers to seek alternative preservation systems.

4. PHTHALATES AND THEIR EFFECTS

Phthalates are a group of chemical compounds commonly used in cosmetic products as plasticizers and fragrance stabilizers. In cosmetics, phthalates are primarily found in perfumes, deodorants, hair sprays, nail polishes, and lotions, where they help improve product flexibility, durability, and fragrance longevity. Due to their widespread use, phthalates represent one of the most common sources of human exposure to synthetic chemicals through personal care products.

Scientific evidence indicates that phthalates can enter the human body through dermal absorption and inhalation. Once absorbed, these compounds may interfere with the endocrine system by altering hormone production and regulation. Numerous studies have identified phthalates as endocrine disruptors, capable of affecting reproductive health in both males and females. Reported effects include reduced fertility, altered hormone levels, and developmental abnormalities, particularly when exposure occurs during critical periods such as pregnancy.

Certain phthalates, including diethyl phthalate (DEP), dibutyl phthalate (DBP), and di(2-ethylhexyl) phthalate (DEHP), have been associated with increased health risks. Research has shown correlations between phthalate exposure and adverse reproductive outcomes, as well as potential effects on fetal development. These findings have prompted stricter regulatory measures and increased scrutiny of cosmetic formulations. Consequently, there is growing emphasis on reducing phthalate use and promoting safer alternatives within the cosmetic industry.

5. FORMALDEHYDE AND FORMALDEHYDE-RELEASING AGENTS

Formaldehyde is a highly reactive chemical compound known for its strong antimicrobial properties. Due to its toxicity and carcinogenic potential, the direct use of formaldehyde in cosmetic products is prohibited in many countries. However, formaldehyde-releasing agents are still present in certain cosmetic formulations, where they function as preservatives by gradually releasing small amounts of formaldehyde over time. Common formaldehyde releasers include DMDM hydantoin, quaternium-15, diazolidinyl urea, and imidazolidinyl urea.

These substances are most frequently found in shampoos, conditioners, liquid soaps, nail products, and hair-straightening treatments. Their use is primarily intended to prevent microbial contamination and extend product shelf life. Despite their functional benefits, formaldehyde-releasing agents raise significant safety concerns due to the continuous low-level exposure they may cause during regular cosmetic use.

Exposure to formaldehyde and its releasing agents has been associated with a range of adverse health effects. Short-term exposure may lead to skin irritation, allergic contact dermatitis, and respiratory discomfort, particularly in individuals with sensitive skin or pre-existing conditions. Long-term or repeated exposure has raised concerns regarding its potential carcinogenic effects, especially through inhalation. As a result, regulatory authorities have imposed strict concentration limits and labeling requirements for products containing formaldehyde-releasing preservatives, while encouraging the development of safer alternative preservation systems.

6. SURFACTANTS (SLS AND SIMILAR COMPOUNDS)

Surfactants are essential components of many cosmetic and personal care products due to their ability to reduce surface tension and enhance cleansing performance. Sodium lauryl sulfate (SLS) and similar compounds are widely used in shampoos, facial cleansers, body washes, and toothpaste because of their strong foaming and detergent properties. These substances effectively remove dirt, oil, and impurities from the skin and hair, contributing to a feeling of cleanliness.

Despite their effectiveness, SLS and related surfactants have been associated with adverse skin effects, particularly when used frequently or in high concentrations. One of the primary concerns is their ability to disrupt the skin's natural lipid barrier, which plays a crucial role in maintaining hydration and protecting against external irritants. Damage to this barrier can lead to increased transepidermal water loss and heightened skin sensitivity.

Skin-related side effects linked to SLS exposure include dryness, redness, itching, and irritation. Individuals with sensitive skin, eczema, or other dermatological conditions may experience exacerbated symptoms. In response to these concerns, many manufacturers have begun replacing SLS with milder surfactants and promoting sulfate-free formulations. This shift reflects growing consumer awareness and the cosmetic industry's efforts to balance product performance with skin safety.

7. FORMALDEHYDE AND FORMALDEHYDE-RELEASING AGENTS

Formaldehyde is a volatile organic compound with strong antimicrobial properties, which has led to its historical use as a preservative. However, due to its high toxicity and classification as a potential human carcinogen, the direct addition of formaldehyde to cosmetic products is strictly regulated or banned in many countries. Despite this, formaldehyde-releasing agents are still used in certain cosmetic formulations as indirect preservatives.

These compounds release small amounts of formaldehyde gradually to inhibit microbial growth and extend product shelf life. Common formaldehyde-releasing agents found in cosmetics include DMDM hydantoin, quaternium-15, diazolidinyl urea, and imidazolidinyl urea. They are frequently present in shampoos, liquid soaps, conditioners, nail products, and hair treatment formulations, particularly in products with high water content.

Health hazards associated with formaldehyde exposure include skin irritation, allergic contact dermatitis, and respiratory discomfort. Individuals with sensitive skin or pre-existing dermatological conditions may be particularly vulnerable. Prolonged or repeated exposure, especially through inhalation, has raised concerns regarding carcinogenic risk. As a result, regulatory agencies require strict concentration limits and clear labeling of formaldehyde-releasing substances, while encouraging manufacturers to adopt safer preservation alternatives.

8. SURFACTANTS (SLS AND SIMILAR COMPOUNDS)

Surfactants are essential ingredients in cosmetic and personal care products due to their cleansing and emulsifying properties. Sodium lauryl sulfate (SLS) and related compounds are commonly used in shampoos, facial cleansers, body washes, and toothpaste to enhance foaming and improve the removal of oils, dirt, and impurities from the skin and hair.

The role of surfactants in cosmetic formulations is to ensure effective cleaning while maintaining product stability and consumer satisfaction. However, strong surfactants such as SLS can negatively affect the skin's protective barrier. By removing natural lipids from the skin surface, these compounds may disrupt the balance between hydration and protection.

Skin-related side effects associated with SLS and similar surfactants include dryness, redness, itching, irritation, and increased sensitivity. In individuals with conditions such as eczema or atopic dermatitis, these effects may be more pronounced. In response to growing safety concerns, many cosmetic manufacturers have shifted toward milder surfactants and sulfate-free formulations to reduce irritation while maintaining cleansing efficacy.

9. FRAGRANCES AND ALLERGENS

Fragrances are widely used in cosmetic products to enhance sensory appeal and improve consumer acceptance. However, fragrance formulations often consist of complex mixtures containing dozens or even hundreds of chemical compounds. Due to intellectual property protection, manufacturers are not required to disclose all individual fragrance ingredients, which are often listed collectively under the term "fragrance" or "parfum" on product labels.

This lack of transparency poses hidden risks, as fragrance mixtures may contain substances capable of causing allergic reactions or skin sensitization. Fragrances are among the most common causes of contact dermatitis associated with cosmetic use. Repeated exposure can increase sensitivity over time, even in individuals without prior allergic history.

Common allergenic fragrance substances include limonene, linalool, eugenol, geraniol, and coumarin. When oxidized, these compounds may become more allergenic and trigger adverse skin reactions. Regulatory authorities in several regions require the labeling of specific fragrance allergens when present above certain concentrations. Nevertheless, fragrance-related sensitivity remains a significant concern, highlighting the need for improved labeling transparency and the development of hypoallergenic and fragrance-free cosmetic alternatives.

10. LABELING AND CONSUMER AWARENESS

Product labeling plays a crucial role in ensuring cosmetic safety and enabling consumers to make informed purchasing decisions. Accurate and transparent labeling allows users to identify potentially harmful substances and assess the suitability of products for their individual needs. However, transparency problems remain a significant challenge within the cosmetic industry.

In many cases, cosmetic labels do not clearly indicate the concentration of ingredients, making it difficult for consumers to evaluate potential health risks. Additionally, certain components, such as fragrance mixtures, are often listed under generic terms like "fragrance" or "parfum," which may conceal the presence of allergenic or sensitizing substances. This lack of detailed information limits consumer awareness and reduces the effectiveness of personal risk assessment.

Informed consumer choice is essential for reducing exposure to potentially toxic ingredients. Increased public awareness, combined with clear and standardized labeling practices, can empower consumers to select safer products and encourage manufacturers to adopt more responsible formulation strategies. Educational initiatives and regulatory enforcement play a key role in improving transparency and protecting consumer health.

11. SAFER ALTERNATIVES IN THE COSMETIC INDUSTRY

Growing concerns about the toxicological effects of certain cosmetic ingredients have driven the industry toward the development of safer alternatives. One major trend is the increased use of natural and plant-based ingredients, which are generally perceived as less harmful and more compatible with human skin. Botanical extracts, essential oils, and naturally derived preservatives are increasingly being incorporated into cosmetic formulations.

In addition to natural ingredients, the cosmetic industry is actively exploring innovative preservation systems and mild surfactants that reduce irritation while maintaining product effectiveness. The demand for products labeled as paraben-free, phthalate-free, sulfate-free, and fragrance-free reflects a broader shift toward health-conscious and environmentally responsible cosmetic production.

Industry trends also indicate a growing emphasis on sustainability, ethical sourcing, and green chemistry principles. These developments not only enhance product safety but also contribute to consumer trust and long-term public health protection. Continuous research and regulatory oversight are essential to ensure that alternative ingredients provide genuine safety benefits without unintended risks.

12. CONCLUSION

This study has critically examined the presence of potentially toxic substances in cosmetic products, focusing on commonly used chemical components such as parabens, phthalates, formaldehyde-releasing agents, surfactants, and fragrance compounds. The analysis highlights that long-term and repeated exposure to certain cosmetic ingredients may pose health risks, including endocrine disruption, skin irritation, allergic reactions, and systemic effects.

The findings emphasize the importance of transparent labeling, informed consumer choice, and stricter regulatory control to minimize these risks. Consumers are encouraged to carefully read product labels, avoid ingredients associated with known health concerns, and prefer products formulated with safer alternatives. At the industry level, manufacturers should prioritize the development of non-toxic, hypoallergenic, and environmentally friendly formulations.

In conclusion, improving cosmetic safety requires a collaborative approach involving regulatory authorities, industry stakeholders, and consumers. By promoting transparency, encouraging innovation, and increasing public awareness, the cosmetic industry can move toward safer and more sustainable practices that protect both human health and the environment.

References

Ababneh, F. A., & Al-Momani, I. F. (2018). Assessments of toxic heavy metals contamination in cosmetic products. *Environmental Forensics*, *19*(2), 134-142.

Akhtar, A., Kazi, T. G., Afridi, H. I., & Khan, M. (2022). Human exposure to toxic elements through facial cosmetic products: Dermal risk assessment. *Regulatory toxicology and pharmacology*, *131*, 105145.

Bilal, M., Mehmood, S., & Iqbal, H. M. (2020). The beast of beauty: environmental and health concerns of toxic components in cosmetics. *Cosmetics*, *7*(1), 13.

Indriaty, S., Hidayati, N. R., & Bachtiar, A. (2018). *Health risks of cosmetic products containing mercury and training on cosmetic registration checking at Gunung Jati Hospital, Cirebon*. **Surya Masyarakat Journal, 1**(1), 8–11.

Kaličanin, B., & Velimirović, D. (2016). A study of the possible harmful effects of cosmetic beauty products on human health. *Biological trace element research*, *170*(2), 476-484.

Kilic, S., Kilic, M., & Soylak, M. (2021). The determination of toxic metals in some traditional cosmetic products and health risk assessment. *Biological trace element research*, *199*(6), 2272-2277.

Lestari, R. D., & Widayati, A. (2022). *Profile of cosmetic use among female adolescents in Indonesian vocational high schools in Yogyakarta*. **Pharmaceutical Journal, 18**(1), 8–16.

Salvador, A., & Chisvert, A. (Eds.). (2011). *Analysis of cosmetic products*. Elsevier.

Supriningrum, R., & Jubaidah, S. (2019). *Counseling on safe cosmetics and identification of mercury in cosmetic products*. **Mahakam Community Service Journal, 3**(2), 136.

Xocayev, V., & Kərimova, D. (n.d.). *The importance of parabens in the cosmetic industry*. Unpublished manuscript.

Zahejsky, J. (2006). *External dermatological therapy and cosmetics: Clinical, physiological, and biological perspectives*. Grada Publishing.

Received: 11.15.2025
Revised: 11.20.2025
Accepted: 12.10.2025
Published: 12.13.2025

Luminis Applied Science and Engineering
ISSN: 3030-1831
Vol 2, No 4, 2025

Substances Migrating from Plastic Products into the Human Body and Their Effects on Human Health

Sevinc Hüseynli
[1] Huseynli, S. Nakhchivan State University, Azerbaijan. Email: sevinchuseynli028@gmail.com. ORCID: https://orcid.org/0009-0004-6881-3937.

https://doi.org/10.69760/lumin.2025004003

Abstract; This study examines the toxicological effects of substances migrating from commonly used plastic products into the human body, with particular emphasis on endocrine-disrupting chemicals (EDCs) such as bisphenol A (BPA) and phthalates. Based on a comprehensive review of international scientific literature published between 2002 and 2021, the research analyzes the sources of human exposure, metabolic pathways, and biological mechanisms through which these chemicals affect human health. The findings indicate that both BPA and phthalates can exert significant biological effects even at very low exposure levels, particularly during critical developmental periods such as pregnancy and early childhood. Evidence suggests that perinatal exposure to BPA may alter fetal epigenetic programming, increasing the risk of metabolic disorders, cardiovascular diseases, and developmental abnormalities later in life. Phthalates, on the other hand, are strongly associated with anti-androgenic effects and reproductive dysfunction. The study highlights ongoing regulatory challenges related to low-dose exposure and non-monotonic dose–response relationships, emphasizing the need for stricter control measures, increased public awareness, and effective strategies to reduce human exposure to these chemicals.

Keywords: endocrine-disrupting chemicals, bisphenol A, phthalates, plastic products, human health

1. INTRODUCTION

Plastic products have become essential in modern life due to their low cost, durability, and wide range of applications. They are commonly used in food packaging, water bottles, household containers, medical devices, and many daily consumer goods. Because of this constant and long-term contact with plastic materials, human exposure to plastic-related chemicals has become increasingly relevant from a public health perspective.

In recent decades, scientific attention has focused on endocrine-disrupting chemicals (EDCs) associated with plastics, especially bisphenol A (BPA) and phthalates. EDCs are substances that can interfere with the normal functioning of the hormonal system by mimicking natural hormones, blocking hormone receptors, or altering hormone synthesis and metabolism. Even low-level exposure may contribute to adverse outcomes, and concerns are stronger for vulnerable groups such as pregnant women, infants, and children. Research has linked EDC exposure to reproductive problems, metabolic disorders, immune changes, and developmental effects, which has increased public and regulatory concern worldwide.

The aim of this study is to analyze the toxicological effects of EDCs migrating from plastic products into the human body, with a focus on BPA and phthalates. The study reviews evidence on sources of exposure, mechanisms of action, metabolism, and possible clinical outcomes. It also discusses the challenges in risk assessment and regulatory decision-making, especially regarding low-dose exposure and long-term health impacts. Overall, the study provides an evidence-based overview intended to support public awareness and encourage strategies that reduce exposure to harmful plastic-related chemicals.

2. PLASTICS AND CHEMICAL ADDITIVES

Plastics are not single pure substances; they are manufactured materials that often require chemical additives to achieve specific functional properties. Additives are used to improve flexibility, durability, transparency, heat resistance, color, and stability. For example, phthalates are commonly added as plasticizers to make plastics softer and more flexible, while BPA is used in producing polycarbonate plastics and epoxy resins that provide strength and protective lining for food containers and cans. Other additives may include flame retardants, antioxidants, stabilizers, and pigments, depending on the intended use of the product.

Although additives improve product performance, they may also create health and environmental concerns because many of these chemicals are not permanently bound to the plastic matrix. Over time, they can be released into the surrounding environment through processes such as heating, mechanical wear, aging, or contact with fats and oils. This release can occur during production, daily use, storage, or disposal of plastic materials. As a result, additives can migrate into food and beverages from packaging, enter indoor air and dust, and ultimately reach the human body through ingestion, inhalation, or skin contact.

The migration of plastic additives is influenced by several factors, including temperature, duration of contact, the type of plastic, the chemical characteristics of the additive, and the nature of the contacted material (e.g., oily or acidic foods). Therefore, understanding how additives are used in plastics and how they migrate into the environment and the human body is essential for evaluating potential risks and developing effective prevention strategies.

3. ENDOCRINE-DISRUPTING CHEMICALS (EDCS)

Endocrine-disrupting chemicals (EDCs) are exogenous substances that can interfere with the normal functioning of the endocrine system. They may **mimic** natural hormones, **block** hormone receptors, or **alter** hormone synthesis, transport, metabolism, and elimination, thereby disturbing hormonal signaling and homeostasis (Rogers et al., 2013). In plastic-related exposure, EDCs are especially important because they can be released from consumer products and reach humans through multiple routes, including diet, inhalation of indoor air/dust, and dermal contact (Singh & Pal, 2018).

Definition and general mechanisms of action

EDCs can act through several biological mechanisms. A major pathway involves interaction with nuclear hormone receptors (e.g., estrogen, androgen, thyroid hormone receptors), leading to changes in gene expression and downstream physiological effects. Some EDCs also influence membrane-associated receptors and rapid signaling pathways, or disrupt endocrine function indirectly through oxidative stress and inflammatory pathways (Rogers et al., 2013). Importantly, endocrine systems regulate development, reproduction, metabolism, and immune function; therefore, disruption may produce effects across multiple organ systems rather than in a single target tissue (Rogers et al., 2013).

Health relevance of low-dose exposure

A central concern in EDC research is that **biological effects may occur at low exposure levels**, sometimes showing **non-monotonic dose–response** patterns (i.e., effects that do not increase linearly with dose). This complicates risk assessment and can create uncertainty in regulatory decisions, especially when exposure is chronic and occurs during sensitive life stages such as fetal and early childhood development (Vom Saal & Vandenberg, 2021). Evidence from both experimental and human studies has supported the need to evaluate real-world, long-term exposure scenarios rather than focusing only on high-dose toxicology models (Tsai, 2007; Vom Saal & Vandenberg, 2021).

4. BISPHENOL A (BPA)

Bisphenol A (BPA) is one of the most widely studied plastic-associated EDCs. It is primarily used in the production of **polycarbonate plastics** and **epoxy resins**, materials valued for durability and clarity and commonly applied in food-contact and household plastic-related materials (Tsai, 2007; Schug & Birnbaum, 2014). Because of its chemical structure, BPA can exhibit estrogen-like activity and may influence endocrine-regulated processes (Vom Saal & Vandenberg, 2021).

Sources of BPA in plastic products

BPA exposure is strongly linked to products and materials made with polycarbonate plastics and epoxy resin coatings, including plastic food-contact items and certain packaging-related applications (Schug & Birnbaum, 2014; Tsai, 2007). Migration tends to increase under conditions such as **heat**, prolonged contact time, and contact with foods or liquids that facilitate leaching, making dietary intake a major exposure route in everyday life (Tsai, 2007; Singh & Pal, 2018).

Metabolism and exposure pathways

After entering the body—most commonly through ingestion—BPA undergoes metabolic processing, including conjugation pathways (e.g., glucuronidation), and is then eliminated. However, even with metabolism, measurable exposure can still occur in population studies, and the timing of exposure may be critical for biological outcomes (Völkel et al., 2002; Tsai, 2007). In addition to dietary intake, exposure may also occur through contact with contaminated dust and through dermal pathways in certain contexts (Singh & Pal, 2018).

Endocrine, metabolic, and developmental effects

BPA is associated with endocrine-related outcomes because it can interact with estrogen signaling and other endocrine pathways (Vom Saal & Vandenberg, 2021). Research has discussed links between BPA exposure and **metabolic outcomes** (such as pathways contributing to obesity-related risk) and broader multi-system effects, particularly when exposure occurs during early development (Tsai, 2007; Sarathi et al., 2021). Experimental evidence has also reported endocrine-related changes in animal models consistent with hormonal disruption mechanisms (Vom Saal et al., 1998). Overall, the literature supports continued attention to BPA as a public health issue, with particular concern for **prenatal and early-life exposure windows** (Sarathi et al., 2021; Vom Saal & Vandenberg, 2021).

5. PHTHALATES

Phthalates are a large group of chemicals primarily used as **plasticizers**, added to plastics to increase flexibility, softness, and durability. They are widely used in many consumer and industrial plastic products, which contributes to widespread human exposure (Kamrin, 2009; Yıldıztekin et al., n.d.). A key issue is that phthalates are often **not chemically bound** to the plastic polymer matrix, making them more prone to release during use, aging, and disposal processes (Kamrin, 2009; Singh & Pal, 2018).

Use of phthalates as plasticizers

Phthalates are used to modify physical properties of plastics and are found in a variety of applications, including flexible plastic materials used in household items and certain product components. Their extensive use increases the probability of continuous low-level exposure over time (Kamrin, 2009; Yıldıztekin et al., n.d.).

Routes of human exposure

Human exposure to phthalates occurs through multiple pathways. **Ingestion** can occur via food and beverages contaminated through contact with phthalate-containing materials, while **inhalation** and **dust ingestion** are relevant in indoor environments. **Dermal exposure** may also occur through contact with certain consumer products and materials (Singh & Pal, 2018; Kamrin, 2009). Because these exposures can be frequent and chronic, population-level exposure is a significant public health concern (Kamrin, 2009).

Reproductive and endocrine toxicity

Phthalates are strongly discussed in the literature for their **endocrine-disrupting potential**, particularly anti-androgenic effects and impacts on reproductive development and function. Research has emphasized risks related to developmental exposure and possible reproductive outcomes, making sensitive periods (prenatal and early childhood) a major focus of concern (Kamrin, 2009; Yıldıztekin et al., n.d.). These findings have supported calls for stronger exposure reduction strategies and more cautious regulatory assumptions in risk assessment (Kamrin, 2009).

6. ROUTES OF HUMAN EXPOSURE

Human exposure to BPA and phthalates occurs through **multiple everyday pathways**, which makes these chemicals a continuous public health concern. Because plastics are used in food systems, household products, and medical settings, exposure is often **chronic** and may affect all age groups, including vulnerable populations (Singh & Pal, 2018; Kamrin, 2009).

Food packaging and containers

Dietary intake is considered a major exposure route, especially when plastic materials come into contact with food and beverages. BPA migration is strongly associated with food-contact materials that use polycarbonate plastics and epoxy resin coatings. Conditions such as **heating, long storage time, and contact with fatty foods** can increase the release of additives into food, raising the likelihood of ingestion (Tsai, 2007; Singh & Pal, 2018). For phthalates, migration can occur from flexible plastic packaging and processing materials, making food-related exposure an ongoing concern in daily life (Kamrin, 2009).

Infant and child products

Infants and children represent a **high-risk group** due to developmental sensitivity and relatively higher exposure per body weight. Plastic feeding items, toys, and other child-related products can contribute to exposure through **hand-to-mouth behavior**, chewing, and prolonged contact. Even when products are marketed as safer, real-life exposure can still occur via household plastics and packaging used around infants (Singh & Pal, 2018). This is particularly important because early-life exposure windows are often considered critical for endocrine-related outcomes (Vom Saal & Vandenberg, 2021).

Cosmetics, medical devices, and household items

In addition to diet, exposure may occur via **indoor environments** and product contact. Phthalates have been widely discussed in relation to flexible plastics used in household materials; exposure may occur through **inhalation and ingestion of indoor dust** as well as dermal contact (Kamrin, 2009; Singh & Pal, 2018). Medical contexts are also relevant because plastic-based devices and tubing can contain additives, potentially contributing to exposure in clinical settings (Singh & Pal, 2018). Overall, these routes demonstrate that exposure is not limited to a single source, which complicates risk reduction and regulation (Kamrin, 2009).

7. HEALTH EFFECTS OF BPA AND PHTHALATES

The health relevance of BPA and phthalates is linked to their classification as endocrine-disrupting chemicals and their potential to influence **reproductive, immune, and metabolic systems**. Evidence summarized in major reviews suggests that effects may occur even at low exposure levels, and outcomes may depend strongly on timing and duration of exposure (Tsai, 2007; Vom Saal & Vandenberg, 2021).

Reproductive and endocrine disorders

Both BPA and phthalates have been associated with endocrine-related effects due to their ability to interfere with hormone signaling pathways. BPA is often discussed for estrogen-like activity and broader endocrine interactions, while phthalates are widely recognized for anti-androgenic concerns in reproductive development (Kamrin, 2009; Vom Saal & Vandenberg, 2021). Because endocrine systems regulate fertility, puberty timing, and reproductive tissue development, even subtle disruptions may have clinically relevant consequences, particularly when exposure occurs during sensitive developmental periods (Vom Saal & Vandenberg, 2021).

Immune system modulation

EDCs may also influence immune function. Mechanistic and review-level evidence has emphasized that BPA can modulate immune responses through endocrine-immune interactions and changes in immune signaling pathways (Rogers et al., 2013). Such modulation may contribute to altered inflammatory responses or immune balance, although the exact clinical implications may vary depending on exposure levels and individual susceptibility (Rogers et al., 2013). Concerns about children's vulnerability are also reflected in pediatric-focused discussions of BPA's multi-system relevance (Sarathi et al., 2021).

Metabolic effects (obesity, diabetes)

Metabolic outcomes are another major area of concern. Reviews have discussed links between BPA exposure and metabolic disruption, including pathways relevant to weight regulation and cardiometabolic risk (Tsai, 2007; Vom Saal & Vandenberg, 2021). Phthalates have similarly been discussed in public health literature due to widespread exposure and potential endocrine-related impacts that may contribute to metabolic dysregulation (Kamrin, 2009). These findings support the importance of evaluating long-term, real-world exposure patterns rather than focusing only on acute toxicity (Tsai, 2007).

8. PRENATAL AND EPIGENETIC EFFECTS

Prenatal and early-life exposure is repeatedly highlighted as a critical concern in the EDC literature, because fetal and infant development depends on precise endocrine signaling. Disruptions during these periods may have **long-lasting consequences**, potentially influencing disease risk later in life (Vom Saal & Vandenberg, 2021).

Perinatal exposure and fetal programming

Perinatal exposure refers to exposure during pregnancy and early postnatal life. Reviews emphasize that BPA exposure during developmental windows may affect biological programming processes that shape endocrine and metabolic trajectories (Tsai, 2007; Vom Saal & Vandenberg, 2021). In addition, immune-related pathways may be affected during development, which is relevant because immune maturation and endocrine regulation are closely connected (Rogers et al., 2013). Although research continues to refine mechanisms, developmental timing is consistently treated as a key factor in interpreting risk (Vom Saal & Vandenberg, 2021).

Long-term health risks in childhood and adulthood

Long-term outcomes discussed in the literature include increased vulnerability to endocrine and metabolic disorders across the lifespan, with particular attention to childhood outcomes because early exposures may manifest as developmental and systemic changes (Sarathi et al., 2021; Vom Saal & Vandenberg, 2021). These concerns reinforce the need for prevention strategies that prioritize exposure reduction in pregnant women, infants, and children, while also supporting broader population-level risk reduction given the widespread nature of plastic-related exposure (Singh & Pal, 2018; Kamrin, 2009).

9. REGULATORY ISSUES AND SCIENTIFIC CONTROVERSIES

Regulating BPA and phthalates remains challenging because endocrine-disrupting chemicals may not follow the classic toxicology principle that “the dose makes the poison” in a simple linear way. A major scientific controversy concerns **low-dose effects** and **non-monotonic dose–response** relationships, meaning that measurable biological effects can occur at low exposure levels and may not increase consistently as dose increases (Vom Saal & Vandenberg, 2021; Tsai, 2007). This pattern complicates standard risk assessment models that often rely on higher-dose testing and assume predictable dose–response trends.

Another area of debate involves differences between **scientific evidence** and **regulatory assumptions**. Some regulatory frameworks may place greater emphasis on traditional toxicity endpoints and thresholds, while many researchers argue that endocrine endpoints, developmental timing, and chronic exposure scenarios require a more precautionary approach (Vom Saal & Vandenberg, 2021). In addition, because exposure occurs from multiple sources simultaneously, assessing “real-life” cumulative risk is difficult, which can lead to gaps between laboratory findings and regulatory decisions (Kamrin, 2009; Singh & Pal, 2018). These issues help explain why different institutions and countries may adopt different limits, restrictions, or labeling requirements for the same chemical groups.

10. PUBLIC HEALTH IMPLICATIONS

The public health impact of BPA and phthalates is amplified by their **widespread presence** in consumer products and the resulting **continuous exposure** in the general population (Singh & Pal, 2018; Kamrin, 2009). Because exposure can occur through food packaging, household dust, consumer products, and medical settings, complete avoidance is difficult, making prevention strategies a public health priority rather than only an individual responsibility (Singh & Pal, 2018).

Vulnerable populations

Vulnerability is strongly influenced by developmental and physiological factors. **Pregnant women, fetuses, infants, and children** are often highlighted as higher-risk groups because endocrine signaling plays a critical role in growth and development, and exposure per body weight may be higher in early life (Vom Saal & Vandenberg, 2021; Sarathi et al., 2021). Individuals with pre-existing endocrine or immune conditions may also be more sensitive to disruption, although susceptibility can vary across populations (Rogers et al., 2013).

Need for risk reduction strategies

Given the broad exposure pathways, effective risk reduction requires coordinated action across consumers, manufacturers, and regulators. Public health strategies should address exposure sources at the population level, especially in food-contact materials and child-related products, where everyday contact is frequent and the potential consequences may be long-term (Kamrin, 2009; Singh & Pal, 2018).

11. RECOMMENDATIONS

Reducing consumer exposure

Practical steps can help lower exposure to BPA and phthalates in daily life. Consumers can reduce risk by limiting heating of food in plastic containers, avoiding prolonged storage of hot or fatty foods in plastics, preferring glass or stainless-steel alternatives when possible, and paying attention to product safety labeling—especially for infant and child products (Singh & Pal, 2018; Tsai, 2007). Reducing indoor dust exposure through regular cleaning and ventilation may also be beneficial, as indoor environments can contribute to chronic exposure pathways (Singh & Pal, 2018).

Policy and regulatory improvements

Regulatory bodies should consider the evolving evidence on endocrine disruption, developmental timing, and low-dose effects. Updating risk assessment methods to better reflect non-monotonic dose–response patterns and cumulative exposure would strengthen protection (Vom Saal & Vandenberg, 2021). Stronger regulation of food-contact materials, improved safety standards for child-related products, and clear disclosure requirements for plastic additives can also reduce population-level exposure (Kamrin, 2009; Singh & Pal, 2018).

Public awareness and education

Public education is essential for translating scientific findings into safer everyday practices. Awareness campaigns and health communication can help consumers understand exposure routes and safer alternatives without creating misinformation or panic. Educational efforts are especially important for families, pregnant women, and caregivers, where risk reduction may have long-term benefits for children's health outcomes (Sarathi et al., 2021; Singh & Pal, 2018).

12. CONCLUSION

This literature-based analysis demonstrates that endocrine-disrupting chemicals migrating from plastic products—particularly BPA and phthalates—represent a significant and complex health concern. The reviewed evidence indicates that these substances may exert biological effects at low exposure levels, influence endocrine regulation, and contribute to reproductive, immune, and metabolic outcomes, especially when exposure occurs during sensitive developmental periods (Rogers et al., 2013; Tsai, 2007; Vom Saal & Vandenberg, 2021). Exposure is widespread and occurs through multiple routes, including food packaging, household environments, and consumer products, which increases the relevance of the issue for public health (Singh & Pal, 2018; Kamrin, 2009).

Preventive measures are therefore essential. Reducing exposure requires a combined approach: informed consumer behavior, safer product design and substitution of harmful additives, and regulatory frameworks that reflect modern evidence on endocrine disruption and real-world exposure patterns (Vom Saal & Vandenberg, 2021; Singh & Pal, 2018). Future research should continue improving understanding of chronic low-dose exposure, mixture effects, and developmental vulnerability, while regulatory systems should adapt to scientific advances to ensure more effective long-term protection of human health.

REFERENCES

Kamrin, M. A. (2009). Phthalate risks, regulation, and public health. *Journal of Toxicology and Environmental Health, Part B, 12*(3), 157–174.

Rogers, A. J., Metz, R. P., & Yong, V. W. (2013). Endocrine-disrupting chemicals and immune responses: Focus on bisphenol A and its potential mechanisms. *Molecular Immunology, 53*(4), 329–338.

Sarathi, N., et al. (2021). Bisphenol A and its effects on organ systems in children. *European Journal of Pediatrics, 180*(11), 3327–3335.

Schug, T. T., & Birnbaum, L. S. (2014). Effects of bisphenol A on human health. In *Toxins in food packaging and household plastics* (pp. 46–57). Springer.

Singh, M., & Pal, R. (2018). Role of plastics on human health. *Indian Journal of Pediatrics, 85*(7), 570–576.

Soni, R., et al. (2018). Role of plastics on human health. *Indian Journal of Pediatrics, 85*(7), 570–576.

Tsai, W. T. (2007). Human health risk from environmental exposure to bisphenol A: An overview. *Reviews in Environmental Contamination and Toxicology, 193*, 137–147.

Turan Miral, M. (n.d.). *Invisible danger: Endocrine-disrupting chemicals*. Istanbul Kultur University.

Völkel, W., Colnot, T., Csanády, G. A., Filser, J. G., & Dekant, W. (2002). Metabolism and kinetics of bisphenol A in humans following oral administration at a potential low dose. *Chemical Research in Toxicology, 15*(10), 1281–1287.

Vom Saal, F. S., Cooke, P. S., Silva, E., et al. (1998). Elevated plasma levels of estradiol and bisphenol A in mice fed bisphenol A. *Endocrinology, 139*(2), 701–706.

Vom Saal, F. S., & Vandenberg, L. N. (2021). Update on the health effects of bisphenol A: Numerous reasons for concern. *Endocrinology, 162*(3), bqaa223.

Yıldıztekin, K. G., Erkekoğlu, P., & Koçer-Gümüşel, B. (n.d.). Are plastics a threat to health? An overview of phthalates. *FABAD Journal of Pharmaceutical Sciences, 38*(1), 35–47.

Received: 11.15.2025
Revised: 11.20.2025
Accepted: 12.10.2025
Published: 12.13.2025

Luminis Applied Science and Engineering
ISSN: 3030-1831
Vol 2, No 4, 2025

Molecular and Cellular Mechanisms of Wound Healing in Animals: Biological Dynamics and Therapeutic Innovations

Natavan Abdullayeva
[1] Abdullayeva, N. 1st-year Master's Student in Veterinary Surgery, Nakhchivan State University, Azerbaijan. ORCID: https://orcid.org/0009-0005-3349-9666

https://doi.org/10.69760/lumin.2025004004

Abstract; Wound healing in animals is a highly complex and dynamic biological process that involves coordinated cellular, molecular, and tissue-level responses aimed at restoring structural and functional integrity after injury. This study examines the biological regulation of wound healing in animals, with particular emphasis on the sequential phases of hemostasis, inflammation, proliferation, and remodeling. Clinical and experimental observations were conducted on farm animals with traumatic, surgical, purulent, and necrotic wounds to evaluate healing dynamics under different treatment approaches. The application of bioactive collagen-based dressings and platelet-rich plasma (PRP) therapy significantly reduced microbial contamination, enhanced fibroblast activity, promoted angiogenesis, and accelerated epithelialization compared with conventional antiseptic treatments. Histological and microbiological findings confirmed improved tissue organization and faster wound closure in the experimental group. The results highlight the importance of understanding wound healing biology for optimizing therapeutic strategies and demonstrate the potential of innovative bioactive treatments in improving clinical outcomes in veterinary practice.

***Keywords**: wound healing, bioactive dressings, epithelialization, veterinary surgery*

1. INTRODUCTION

Wound healing is a fundamental process in veterinary medicine, as injuries to the skin and underlying tissues are among the most frequently encountered clinical problems in farm and domestic animals. Effective wound management is essential not only for restoring tissue integrity but also for preventing infections, reducing pain, and maintaining animal welfare. Delayed or impaired wound healing can lead to serious complications, including chronic infections, systemic illness, and decreased productivity, particularly in livestock species.

Wounds in animals arise from a variety of causes. In farm animals, common sources include mechanical trauma, housing and equipment-related injuries, handling and transportation accidents, and surgical interventions. Domestic animals are frequently affected by bite wounds, lacerations, burns, and post-operative complications. Environmental factors, poor hygiene, and management practices may further increase the risk of wound contamination and delayed healing.

The clinical and economic significance of wound healing is especially pronounced in agricultural settings. Prolonged recovery times can result in reduced growth rates, decreased milk or meat production, increased veterinary costs, and, in severe cases, loss of animals. From a clinical perspective, understanding the biological mechanisms underlying wound healing is critical for selecting appropriate treatment strategies and improving therapeutic outcomes. Therefore, wound healing biology remains a key area of interest in both veterinary practice and research.

2. DEFINITION AND CLASSIFICATION OF WOUNDS

A wound is defined as a disruption of the anatomical and functional integrity of tissues caused by physical, chemical, thermal, or biological factors. Proper classification of wounds is essential for determining prognosis and selecting effective treatment approaches.

Based on the nature of injury, wounds are commonly classified as mechanical, thermal, chemical, or biological. Mechanical wounds include incisions, punctures, crush injuries, and lacerations, often resulting from trauma or surgical procedures. Thermal wounds arise from exposure to heat or cold, such as burns and frostbite. Chemical wounds occur following contact with corrosive substances, including acids and alkalis. Biological wounds are caused by microorganisms or parasites and are frequently associated with infection and tissue necrosis.

Wounds are further categorized as acute or chronic. Acute wounds typically follow a predictable healing pattern and resolve within a normal time frame. In contrast, chronic wounds fail to progress through the normal stages of healing and are often associated with persistent inflammation, infection, or underlying systemic disorders. Additionally, wounds may be classified as aseptic or septic, depending on the presence or absence of microbial contamination. Septic wounds present a greater therapeutic challenge and require more intensive management to prevent complications.

3. BIOLOGICAL BASIS OF WOUND HEALING

Wound healing is a complex, multi-phase biological process that involves coordinated interactions among cells, signaling molecules, and structural components of tissues. At the cellular level, key participants include platelets, inflammatory cells, fibroblasts, endothelial cells, and epithelial cells. These cells communicate through the release of cytokines, growth factors, and chemokines that regulate inflammation, cell migration, proliferation, and tissue remodeling.

The extracellular matrix (ECM) plays a crucial role in wound healing by providing structural support and a dynamic scaffold for cell attachment and migration. Components such as collagen, fibronectin, and proteoglycans influence cell behavior and tissue strength. During healing, the ECM undergoes continuous remodeling, allowing newly formed tissue to gradually regain functional integrity.

Wound healing is also regulated by the interaction of the immune, nervous, and endocrine systems. The immune system initiates inflammatory responses and protects against infection, while the nervous system influences vascular responses and cellular activity through neurogenic signaling. Endocrine factors, including hormones and metabolic regulators, modulate cellular functions and energy availability required for tissue repair. The integration of these systems ensures an efficient and coordinated healing response, highlighting the biological complexity underlying wound repair in animals.

4. STAGES OF WOUND HEALING AND KEY INFLUENCING FACTORS

Wound healing in animals is a coordinated, multi-phase process that restores tissue integrity through successive biological stages. Although the phases overlap in time, each stage has dominant cellular activities and specific clinical characteristics. The efficiency of healing depends not only on the biological progression of these stages but also on multiple internal and external factors, including the animal’s physiological condition, nutritional status, wound characteristics, and environmental management.

Hemostasis

Hemostasis begins immediately after injury and serves as the first protective response. Reflex vasoconstriction reduces blood loss, while activated platelets form a temporary plug. The coagulation cascade produces a fibrin network that stabilizes the clot and creates an initial matrix for cell migration. This clot also limits the entry of microorganisms and provides biochemical signals that initiate the inflammatory phase.

Inflammatory phase

The inflammatory phase typically occurs within the first days after injury. Neutrophils migrate into the wound to control microbial contamination and remove debris, followed by macrophages that continue phagocytosis and coordinate tissue repair. Macrophages are particularly important because they release cytokines and growth factors that regulate the transition from inflammation to tissue formation. Excessive or prolonged inflammation, however, may lead to tissue damage and delayed healing.

Proliferative phase

During proliferation, the wound begins to fill with granulation tissue. Fibroblasts proliferate and synthesize collagen and other extracellular matrix components, strengthening the wound structure. At the same time, angiogenesis develops new capillaries to supply oxygen and nutrients. Epithelial cells migrate from the wound edges to restore the surface barrier, a process known as epithelialization. Clinically, this phase is characterized by visible granulation tissue, reduced exudate, and gradual wound contraction.

Remodeling and maturation phase

In the final stage, collagen fibers are reorganized and cross-linked, and vascular density decreases as the tissue becomes more stable. Although tensile strength improves, scar tissue does not fully replicate the original tissue structure. The duration of remodeling may range from weeks to months and is strongly affected by wound severity and systemic conditions.

Factors affecting wound healing in animals

Several factors can accelerate or delay healing. Species differences influence tissue repair capacity and inflammatory responses. Age is also critical, as young animals often heal faster than older ones due to better cell proliferation and circulation. General physiological condition, including endocrine balance and stress levels, affects immune response and tissue regeneration.

Nutrition and immune status are among the most important systemic determinants. Deficiencies in protein, energy, vitamins, and minerals can reduce fibroblast activity, collagen synthesis, and immune defense, increasing susceptibility to infection. Similarly, immunosuppression or metabolic disorders may prolong inflammation and impair granulation and epithelialization.

Local wound factors also play a major role. Large, deep, or highly contaminated wounds require more time to heal and are more likely to become chronic. Poor blood supply, extensive tissue necrosis, and repeated trauma to the wound area can significantly delay progress through the healing stages. Environmental and management conditions—such as hygiene, housing quality, moisture, bedding, and handling practices—may either support clean healing or promote contamination and reinjury.

5. INFECTION AND INFLAMMATION IN WOUNDS

Infection is one of the most common causes of delayed wound healing in veterinary practice. Microbial contamination may occur at the time of injury or during subsequent management. When bacteria multiply in the wound, they intensify inflammatory responses, increase tissue necrosis, and reduce the effectiveness of repair mechanisms.

Microbial contamination and biofilm formation

A major challenge in chronic or non-healing wounds is biofilm formation. Biofilms are structured communities of microorganisms attached to the wound surface and protected by an extracellular matrix. This structure reduces bacterial sensitivity to antiseptics and antibiotics and makes infection more persistent. As a result, wounds with biofilms may show prolonged exudation, persistent odor, weak granulation tissue, and delayed epithelialization.

Role of cytokines and inflammatory mediators

Cytokines and inflammatory mediators regulate both protective and harmful outcomes in wound healing. In a normal response, cytokines recruit immune cells and support tissue repair. However, excessive production of inflammatory mediators can maintain the wound in an inflammatory state, preventing progression to the proliferative and remodeling phases. This imbalance can lead to chronic inflammation, impaired collagen formation, and prolonged healing time.

Impact on delayed healing

Infected wounds typically show increased swelling, heat, pain sensitivity, and purulent discharge. Clinically, infection slows granulation tissue formation, damages newly formed vessels, and interrupts epithelial migration. Therefore, effective control of infection—through debridement, appropriate antiseptics, and targeted therapy—is essential for restoring normal healing dynamics.

6. MATERIALS AND METHODS

Clinical examination and wound modeling

The study involved clinical observation and treatment of mechanically induced traumatic wounds as well as purulent and necrotic open wounds in farm animals. Wounds were assessed by type, depth, size, degree of contamination, and clinical signs such as temperature, edema, and exudate characteristics. Wound healing stages were recorded daily to evaluate progression and response to treatment.

Surgical procedures and treatment protocols

Standard wound management procedures were applied, including cleaning, disinfection, and when necessary, surgical intervention such as debridement to remove necrotic tissue. Treatment was continued for 21 days, and wound dynamics were monitored throughout the study period.

Experimental design and animal grouping

A total of 30 calves were included and divided into two groups:

1. **Control group:** Treated with conventional antiseptics and standard dressings.
2. **Experimental group:** Treated using PRP therapy and bioactive collagen-based dressings.

Evaluation methods included visual clinical assessment, planimetric measurement of wound area, microbiological examination, histological analysis (hematoxylin-eosin staining), and immunohistochemical methods. Outcomes were compared between the two groups to assess differences in epithelialization speed, microbial load, granulation quality, and tissue organization.

7. MODERN TREATMENT APPROACHES

Effective wound management in veterinary practice aims to control bleeding, prevent infection, remove devitalized tissue, and create optimal local conditions for tissue repair. In recent years, modern approaches such as **bioactive dressings** and **platelet-rich plasma (PRP) therapy** have gained attention because they support healing not only through protection but also through direct biological stimulation of repair processes.

Conventional antiseptic and dressing methods

Traditional wound care typically includes mechanical cleaning, disinfection, removal of necrotic tissue when necessary, and application of standard dressings. Antiseptics help reduce microbial load, while dressings protect the wound surface from further contamination and trauma. Although conventional methods are effective in many cases, they may be less successful in wounds with high contamination, necrosis, or prolonged inflammation, where healing often becomes delayed.

Bioactive dressings

Bioactive dressings are designed to provide more than physical coverage. In addition to maintaining an optimal moist environment, they can promote epithelial migration, support granulation tissue formation, and reduce microbial contamination. Collagen-based bioactive dressings, in particular, act as a scaffold for cell adhesion and fibroblast activity, which may enhance collagen deposition and improve tissue organization during the proliferative phase.

Platelet-rich plasma (PRP) therapy

PRP therapy involves the application of a concentrated platelet fraction derived from the animal's own blood. Platelets release multiple growth factors that can stimulate angiogenesis, fibroblast proliferation, extracellular matrix production, and epithelialization. PRP is especially relevant in chronic or complicated wounds because it may shorten the inflammatory phase and accelerate the transition to active tissue repair.

8. EXPERIMENTAL RESULTS

Clinical observations and wound size reduction

During the 21-day observation period, wounds in both groups showed progressive healing; however, the **experimental group (PRP + bioactive dressings)** demonstrated faster improvement in key clinical parameters. Compared with the control group, wounds in the experimental group showed earlier reduction in edema and exudate, cleaner wound beds, and quicker appearance of healthy granulation tissue. Overall, epithelialization was observed to progress approximately **30–40% faster** than in the control group, and necrotic tissue was recorded less frequently.

Histological and microbiological findings

Microbiological examination indicated that the experimental approach reduced wound contamination more effectively, supporting a cleaner local environment for repair. Histological assessment (hematoxylin–eosin staining) showed increased fibroblast activity, denser and more organized collagen fiber deposition, and a higher number of newly formed capillaries (angiogenesis) in the experimental group. These findings corresponded with stronger granulation tissue development and a more active proliferative phase.

Comparison between control and experimental groups

- **Control group:** Healing progressed under standard antiseptic care, but inflammation and exudation tended to persist longer, and epithelial closure was slower.
- **Experimental group:** Faster transition from inflammation to proliferation, improved tissue organization, reduced microbial burden, and accelerated epithelial coverage.

9. DISCUSSION

Interpretation of experimental outcomes

The results indicate that wound healing in animals is strongly influenced by local wound conditions—especially microbial load and moisture balance—as well as by biological stimulation of repair mechanisms. The experimental group's faster epithelialization and improved histological architecture suggest that PRP and bioactive dressings support a more favorable healing trajectory by promoting earlier granulation and more efficient tissue remodeling.

Advantages of bioactive dressings and PRP

Bioactive dressings likely improved outcomes by maintaining an optimal moist environment and supporting fibroblast migration and collagen synthesis through structural scaffolding. PRP therapy likely enhanced healing by delivering growth factors that stimulate angiogenesis and cellular proliferation, improving oxygen and nutrient supply to the wound bed and accelerating repair. The combined use of both approaches may therefore provide a synergistic benefit, particularly for traumatic, necrotic, and purulent wounds where classical methods may be slower.

Comparison with previous studies

The observed improvements align with broader veterinary surgical literature emphasizing the importance of moisture-balanced wound environments, microbial control, and biologically active therapies for enhanced regeneration. The findings support the growing clinical trend toward integrating regenerative techniques and advanced dressings into routine veterinary wound management, especially for complicated wounds.

10. CONCLUSION

This study confirms that wound healing in animals is a complex, multi-stage biological process regulated through coordinated cellular and molecular mechanisms across the phases of hemostasis, inflammation, proliferation, and remodeling. The experimental application of **bioactive collagen-based dressings** and **PRP therapy** reduced microbial contamination, promoted fibroblast activity and angiogenesis, improved collagen organization, and significantly accelerated epithelialization compared with conventional antiseptic care.

These results highlight the practical value of combining innovative wound-healing technologies with standard veterinary management. Implementing bioactive dressings and PRP-based strategies can improve clinical outcomes, shorten recovery time, and support animal welfare and productivity, particularly in farm animals with traumatic or infected wounds. Further controlled studies with expanded sample sizes and standardized wound models would strengthen evidence for broader clinical adoption.

REFERENCES

İsgəndərov, T. B. (2011). *Ümumi və xüsusi baytarlıq cərrahiyyəsi*. Gəncə: ADAU nəşriyyatı.

Özaydın, İ. (2024). Cerrahi yara kapatma yöntemleri ve yara sağaltımı. *Technical and Agrarian Sciences, 1*(7), 51–61.

Williams, J., & Moores, A. (2009). *Wound management and reconstruction* (2nd ed., pp. 1–13). Wiley-Blackwell.

Pavletic, M. M. (2010). *Atlas of small animal wound management and reconstructive surgery* (3rd ed., pp. 17–28). Wiley-Blackwell.

Tobias, K. M., & Johnston, S. A. (2012). *Veterinary surgery: Small animal* (pp. 125–134). Elsevier Saunders.

Received: 11.15.2025
Revised: 11.20.2025
Accepted: 12.10.2025
Published: 12.13.2025

Luminis Applied Science and Engineering
ISSN: 3030-1831
Vol 2, No 4, 2025

The Position and Classification of Hydrogen in the Periodic Table: A Comparative and Conceptual Analysis

Günay Ismayılova
[1] Ismayilova, G. Nakhchivan State University, Nakhchivan, Azerbaijan. Email: gunayismayilovvaa68@gmail.com. ORCID: https://orcid.org/0009-0008-9387-4589

https://doi.org/10.69760/lumin.2025004005

Abstract; Hydrogen occupies a unique and controversial position in the periodic table due to its simple atomic structure and diverse chemical behavior. Although it is traditionally placed at the top of Group 1, hydrogen displays properties that resemble not only alkali metals but also halogens, making its classification problematic. This ongoing debate highlights the limitations of rigid group-based classification within the periodic system. The purpose of this study is to examine the position of hydrogen in the periodic table by analyzing its atomic structure, chemical reactivity, and bonding behavior in comparison with different element groups. The research employs a comparative analytical method, focusing primarily on similarities and differences between hydrogen, alkali metals, and halogens, as well as considering alternative classification models proposed in modern chemistry. The findings indicate that hydrogen cannot be fully integrated into any single group due to its ability to exhibit both metallic and nonmetallic characteristics and to form compounds with varying oxidation states. The study concludes that hydrogen should be regarded as a unique element with a special or independent position in the periodic table, reflecting its exceptional chemical nature and theoretical significance.

***Keywords**: Hydrogen, Periodic table, group similarities, halogens, chemical properties*

1. INTRODUCTION

Hydrogen is the most abundant element in the universe and plays a fundamental role in both chemical reactions and the structure of matter. Despite its simplicity and widespread occurrence, the classification of hydrogen within the periodic table remains one of the most debated issues in chemistry. Unlike most elements, hydrogen exhibits chemical properties that align with more than one group, which challenges traditional approaches to periodic classification.

The classification of elements is essential for understanding periodic trends, predicting chemical behavior, and developing coherent chemical theory. An accurate placement of hydrogen is therefore not only a matter of organization but also a theoretical concern that influences how chemical relationships are interpreted. Historically, hydrogen has been placed in Group 1 due to its single valence electron; however, its nonmetallic nature and ability to gain an electron suggest similarities with halogens as well.

Various scientific viewpoints have been proposed to resolve this issue, including placing hydrogen with alkali metals, aligning it with halogens, or assigning it a separate position. This study aims to address the following questions: Why is hydrogen difficult to classify within a single group? Which group similarities are most chemically significant? And is assigning hydrogen an independent position in the periodic table scientifically justified? By exploring these questions, the article seeks to clarify the unique chemical identity of hydrogen.

2. Atomic Structure and Fundamental Properties of Hydrogen

2.1 Atomic and Isotopic Structure

Hydrogen is the lightest element in the periodic table and has the simplest atomic structure. Its atom consists of a nucleus containing a single proton and one electron occupying the 1s orbital. The most abundant isotope of hydrogen is protium, which has no neutrons. In addition, hydrogen has two other naturally occurring isotopes: deuterium, containing one neutron, and tritium, containing two neutrons. These isotopes differ in mass but exhibit similar chemical behavior, although their physical properties vary. The simplicity of hydrogen's atomic structure plays a key role in its unique chemical characteristics and contributes to the difficulty of its classification within the periodic system.

2.2 Electronic Configuration and Bonding Behavior

The electronic configuration of hydrogen is $1s^1$, meaning it contains one valence electron. This configuration allows hydrogen to participate in chemical bonding by either losing, gaining, or sharing its electron. As a result, hydrogen is capable of forming both ionic and covalent bonds. In reactions with highly electropositive metals, hydrogen can form hydrides in which it exists as a negatively charged ion (H^-). In contrast, when bonded with nonmetals, hydrogen typically forms covalent compounds. This flexible bonding behavior distinguishes hydrogen from most other elements.

2.3 Oxidation States and Reactivity

Hydrogen commonly exhibits oxidation states of +1 and –1, depending on the nature of the elements with which it reacts. In acids and most covalent compounds, hydrogen exists in the +1 oxidation state. In metal hydrides, it appears in the –1 oxidation state. This ability to adopt different oxidation states enables hydrogen to act as both an oxidizing and a reducing agent. Such versatility in reactivity further complicates its placement within a single element group.

2.4 Physical Properties Relevant to Classification

Under standard conditions, hydrogen exists as a colorless, odorless, and tasteless diatomic gas (H_2). It has very low density and melting and boiling points compared to metallic elements. Unlike alkali metals, hydrogen does not exhibit typical metallic properties such as electrical conductivity or malleability. These physical characteristics support its classification as a nonmetal and highlight the limitations of placing hydrogen among metallic elements.

3. HYDROGEN AND GROUP 1 (ALKALI METALS): COMPARATIVE ANALYSIS

3.1 Similarities

Hydrogen shares several important characteristics with alkali metals, which explains its traditional placement above Group 1 in the periodic table. Both hydrogen and alkali metals possess a single valence electron, allowing them to form compounds in which they commonly exhibit a +1 oxidation state. Additionally, hydrogen is positioned directly above alkali metals in the periodic table, suggesting an electronic similarity based on valence structure.

3.2 Differences

Despite these similarities, significant differences exist between hydrogen and alkali metals. Hydrogen is a nonmetal and exists as a diatomic gas under normal conditions, whereas alkali metals are soft, highly reactive solids. Alkali metals display strong metallic character and readily form positively charged ions (M^+), while hydrogen can exist as either a positive or negative ion depending on the reaction. Furthermore, alkali metals predominantly form ionic compounds, whereas hydrogen frequently forms covalent bonds.

3.3 Evaluation

Although hydrogen shares certain electronic features with alkali metals, these similarities are insufficient to justify its full inclusion in Group 1. The absence of metallic properties, its gaseous physical state, and its ability to form both positive and negative ions distinguish hydrogen from true alkali metals. Therefore, while hydrogen's placement above Group 1 has some theoretical basis, it does not fully reflect the element's complex chemical behavior, making this classification incomplete.

4. HYDROGEN AND GROUP 17 (HALOGENS): COMPARATIVE ANALYSIS

4.1 Similarities

Hydrogen shares several notable features with the halogens (Group 17), which is why some chemists have argued that hydrogen could be placed above fluorine rather than above lithium. First, hydrogen is able to gain one electron under certain conditions and form the hydride ion (H^-), corresponding to the –1 oxidation state—an important characteristic of halogens. Second, hydrogen exists in nature as a diatomic molecule (H_2), similar to halogens such as F_2 and Cl_2, which also exist as diatomic molecules in their elemental form. Third, hydrogen demonstrates nonmetallic behavior in many respects, including relatively low density, nonmetallic physical properties, and a strong tendency to form covalent bonds with many nonmetals.

4.2 Differences

Despite these similarities, hydrogen differs from halogens in several fundamental aspects. A key difference is electron affinity: halogens have very high electron affinity and strongly attract electrons, which contributes to their high reactivity. Hydrogen's electron affinity is significantly lower, meaning it does not gain electrons as readily as halogens. Reactivity is another major distinction. Halogens are among the most reactive nonmetals and often react vigorously to form salts with metals, whereas hydrogen's reactivity depends strongly on conditions such as temperature, catalysts, or the presence of specific reactive partners. In addition, the compound types formed by hydrogen are far more diverse than those formed by halogens. While halogens commonly form halides and strong oxidizing compounds, hydrogen forms acids, hydrides, covalent molecular compounds (e.g., water, ammonia, methane), and complex bonding environments such as hydrogen bonding.

4.3 Evaluation

The comparison shows that hydrogen does share some structural and electronic features with halogens, especially its ability to form a –1 oxidation state and its diatomic form. However, the differences in electron affinity, typical reactivity patterns, and the wide variety of compound types formed by hydrogen limit the accuracy of a Group 17 classification. Therefore, placing hydrogen among the halogens may highlight one aspect of its behavior, but it does not fully represent hydrogen's overall chemical identity.

5. ALTERNATIVE CLASSIFICATION PERSPECTIVES

5.1 Hydrogen as a Standalone Element

A widely supported modern approach is to treat hydrogen as a standalone element with a special position in the periodic table. This perspective is based on the fact that hydrogen does not consistently behave like any single group. Its unique combination of electronic simplicity, variable oxidation states, and flexible bonding behavior makes it an exception to typical periodic patterns. As a result, some periodic table designs place hydrogen separately at the top of the table or in a floating position to reflect its exceptional chemical nature.

5.2 Periodic Table Symmetry and Conceptual Models

Some researchers discuss hydrogen's placement using broader conceptual models of periodicity, symmetry, and periodic table design. In such approaches, the periodic table is viewed not only as a list of elements but also as a structured model that reflects repeating chemical relationships. Hydrogen becomes challenging in these models because it disrupts symmetry: its electron configuration suggests one classification, while its chemical behavior suggests multiple. Consequently, alternative periodic table designs—including extended, left-step, or symmetry-based tables—often attempt to give hydrogen a position that improves theoretical consistency, even if it differs from traditional layouts.

5.3 Educational vs. Theoretical Representations

Another important modern viewpoint distinguishes between educational convenience and theoretical accuracy. In many school-level periodic tables, hydrogen is placed above Group 1 because it is simple to explain through valence electron logic (one electron, similar to alkali metals). However, from a theoretical and research perspective, this placement is often considered incomplete because it does not reflect hydrogen's nonmetallic properties and its halogen-like behavior in some reactions. Therefore, educators may prioritize simplicity, while scientists may prioritize a classification that better represents hydrogen's full chemical versatility.

5.4 Summary of Modern Scientific Viewpoints

Modern chemical literature generally recognizes that hydrogen cannot be fully explained by assigning it to either Group 1 or Group 17 alone. While its electronic structure supports similarities with alkali metals, and certain oxidation behaviors resemble halogens, neither grouping accounts for hydrogen's full range of reactivity and bonding. For this reason, many contemporary discussions support presenting hydrogen as a unique element with a special placement in the periodic table. This approach better reflects hydrogen's dual character and preserves the explanatory power of periodic classification without forcing the element into an unsuitable category.

6. THE CLASSIFICATION PROBLEM OF HYDROGEN

Hydrogen is difficult to classify because no single periodic group captures its full chemical behavior. The standard table places hydrogen above Group 1 largely because it has one valence electron ($1s^1$) and often forms compounds where hydrogen is effectively +1. However, hydrogen is not a metal under ordinary conditions and does not show the typical metallic bonding, conductivity, and solid-state properties that characterize alkali metals. At the same time, hydrogen can also occur as H^- (hydride) in ionic metal hydrides, a feature that resembles halogens' tendency to form –1 ions, yet hydrogen's electron-gain tendency and overall reaction patterns do not match the consistently high electron affinity and strong oxidizing behavior typical of Group 17.

From a conceptual standpoint, hydrogen is often treated as a “borderline” element—one whose behavior overlaps multiple families without fully belonging to any of them. Modern discussions emphasize that hydrogen’s dual character (metal-like in some contexts, nonmetal-like in many others) makes it an exception to simplified periodic trends and labels (metal vs. nonmetal; typical oxidation patterns; uniform group chemistry). This is why several classification proposals exist simultaneously, including placement in Group 1, Group 17, dual positioning, or a stand-alone placement designed to reflect its exceptional status.

7. IMPLICATIONS FOR CHEMICAL THEORY AND EDUCATION

Hydrogen’s disputed position shows that the periodic table is not only a chart of atomic numbers but also a theoretical model that tries to summarize chemical relationships. Hydrogen challenges rigid classification because it demonstrates how electron configuration alone cannot always determine “group identity,” especially when bonding diversity and oxidation-state variability are considered. In broader theoretical debates (for example, discussions about metallic/nonmetallic boundaries and periodic trends), hydrogen is frequently used as an example of why chemical categories can be context-dependent rather than absolute.

For chemistry education, this has a practical message: instructors may present hydrogen in Group 1 for introductory simplicity, but students should also learn that professional chemistry recognizes hydrogen as unique and often represented in alternative ways (e.g., shown at the top of both Groups 1 and 17, or placed separately). Using hydrogen as a “case study” can improve learners’ understanding that the periodic table balances pedagogical clarity with scientific nuance, and that multiple representations may be valid depending on the learning goal (trend prediction vs. conceptual accuracy).

8. CONCLUSION

This article addressed a central question in periodic classification: Where does hydrogen most appropriately belong in the periodic table? Comparative analysis shows that hydrogen shares important features with Group 1 (one valence electron; frequent +1 oxidation state) while also displaying meaningful parallels with Group 17 (formation of –1 hydride; diatomic elemental form; nonmetallic character). Nevertheless, major differences in physical nature, electron-gain tendencies, and compound diversity prevent hydrogen from fitting fully into either family.

The evidence supports the view that hydrogen should be treated as a chemically unique element, and that an independent or special placement best communicates its exceptional behavior without forcing it into an imperfect group category. Such a conclusion does not weaken the periodic table; rather, it strengthens it by acknowledging that periodic classification is a powerful model—yet one that must sometimes accommodate exceptional cases like hydrogen.

REFERENCES

Petruševski, V. M., & Cvetković, J. (2018). On the ‘true position’of hydrogen in the periodic table. *Foundations of Chemistry*, *20*(3), 251-260.

Petruševski, V. M., & Cvetković, J. (2017). ON THE'TRUE POSITION'OF HYDROGEN IN THE PERIODIC TABLE. *Contributions. Section of Natural, Mathematical & Biotechnical Sciences*, *38*(1).

Labarca, M. G., & Srivaths, A. (2016). On the placement of hydrogen and helium in the periodic system: a new approach.

Dash, H. H. (1964). Position of hydrogen in the periodic system of elements. *Nature*, *202*(4936), 1001-1003.

Jensen, W. B. (1986). Classification, symmetry and the periodic table. In *Symmetry* (pp. 487-510). Pergamon.

Hensel, F., Slocombe, D. R., & Edwards, P. P. (2015). On the occurrence of metallic character in the periodic table of the chemical elements. *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences*, *373*(2037).

Cao, C., Vernon, R. E., Schwarz, W. E., & Li, J. (2021). Understanding periodic and non-periodic chemistry in periodic tables. *Frontiers in Chemistry*, *8*, 813.

Received: 11.15.2025
Revised: 11.20.2025
Accepted: 12.10.2025
Published: 12.13.2025

Luminis Applied Science and Engineering
ISSN: 3030-1831
Vol 2, No 4, 2025

Engineered Inorganic Adsorbents for Water Remediation: From Surface Modification to Selective Heavy-Metal Capture

Aysun Huseynli, Shahmurad Rustamov
[1] Huseynli, A. Nakhchivan State University, Azerbaijan. Email: aysunhuseynli17@gmail.com. ORCID: https://orcid.org/0009-0009-1757-918X
[2] Rustamov, Sh. Nakhchivan State University, Azerbaijan. Email: shahmuradrustamov58@gmail.com. ORCID: https://orcid.org/0009-0003-5716-3935

https://doi.org/10.69760/lumin.2025004006

Abstract; Inorganic adsorbent materials have become key tools in water purification and industrial wastewater treatment due to their chemical stability, low cost, and strong adsorption performance. This article reviews the adsorption behavior of major inorganic adsorbent groups—zeolites (clinoptilolite), metal oxide nanoparticles (Fe_2O_3 and MnO_2), and functionalized silica—focusing on their structural features, surface chemistry, and pollutant–surface interactions. The main adsorption mechanisms include ion exchange, electrostatic attraction, surface complexation, and, in the case of MnO_2, oxidation-related processes. Comparative analysis indicates that surface modification significantly improves selectivity and capacity, particularly for heavy metal ions such as Pb^{2+}, Cd^{2+}, and Cr species. Isotherm and kinetic interpretations suggest that modified oxides and amine-functionalized silica often follow Langmuir-type behavior with pseudo-second-order kinetics, supporting chemically controlled adsorption. Regeneration studies highlight that many inorganic adsorbents maintain practical efficiency over multiple cycles, strengthening their sustainability and real-world applicability. Overall, modified inorganic nanomaterials show strong potential for long-term use in pollutant removal, especially when designed for selectivity, reusability, and performance under realistic wastewater conditions.

***Keywords**: inorganic adsorbents, heavy metal removal, surface modification, adsorption mechanisms*

1. INTRODUCTION

Water pollution remains a persistent global challenge, largely driven by industrial discharge, mining activities, agricultural runoff, and urban wastewater. Among the most concerning contaminants are **heavy metal ions** (e.g., Pb^{2+}, Cd^{2+}, Cr species), because they are non-biodegradable, can accumulate in ecosystems, and may pose long-term risks to human health and aquatic life. Conventional treatment technologies (precipitation, membrane filtration, or advanced oxidation) can be effective, but they often require high operational costs, complex infrastructure, or generate secondary waste streams. For this reason, **adsorption** continues to be viewed as a practical and scalable strategy for pollutant removal, especially when robust and regenerable adsorbents are available (Wang & Chen, 2009).

In this context, **inorganic adsorbents** have gained strong attention because many of them are **chemically stable**, tolerant to pH variations, and retain structural integrity under harsh water-treatment conditions. Compared with several organic or polymer-based adsorbents, inorganic materials often show better resistance to thermal and chemical degradation and can be regenerated and reused, improving cost-efficiency and sustainability (Kumar & Singh, 2021). Additionally, many inorganic adsorbents—such as zeolites and natural clays—are widely available and relatively inexpensive, making them attractive for large-scale applications (Kılıç et al., 2017).

The aim of this article is to provide a structured overview of **inorganic adsorbent materials** used in water purification, focusing on their key classes (zeolites, metal oxides, and silica-based materials), the dominant **adsorption mechanisms**, and the major factors controlling selectivity and performance. Special attention is given to how **surface modification** and functionalization improve adsorption capacity, kinetics, and reusability in real-world treatment scenarios (Wang & Chen, 2009; Kumar & Singh, 2021).

2. OVERVIEW OF INORGANIC ADSORBENT MATERIALS

Inorganic adsorbents can be broadly categorized into **zeolites**, **metal oxides**, and **silica-based materials**, each offering distinct structural advantages and surface chemistries. Their effectiveness is largely determined by surface area, pore structure, and the availability of active adsorption sites.

Zeolites (e.g., clinoptilolite)

Zeolites are crystalline aluminosilicate minerals characterized by well-defined pore systems and high cation-exchange capacity. **Clinoptilolite**, one of the most widely studied natural zeolites, is particularly valued because it is inexpensive, stable, and capable of removing metal ions through ion exchange and adsorption in its pore network (Kılıç et al., 2017). However, natural zeolites typically show moderate adsorption capacities compared with engineered nanomaterials, and performance can depend strongly on water chemistry and competing ions.

Metal oxides (Fe_2O_3, MnO_2, TiO_2, etc.)

Metal oxides—especially in nano- or micro-structured forms—are widely used due to their reactive surfaces, rich functional groups, and strong affinity for metal ions. **Fe_2O_3 (iron oxide)** is often highlighted for rapid adsorption and practical separation advantages (e.g., magnetic behavior in some iron oxide systems). **MnO_2** is frequently discussed for its dual role: adsorption plus oxidation-related processes that can enhance removal of certain contaminants and dyes. Other oxides such as **TiO_2** may be applied as adsorbents or as components of composite systems designed for combined adsorption and catalytic functions (Wang & Chen, 2009).

Silica-based adsorbents and functionalized silica

Silica materials (including mesoporous silica) are valued for their high surface area, tunable pore structure, and ease of **surface functionalization**. When silica is modified with functional groups such as amines ($-NH_2$) or thiols (–SH), it can show substantially improved selectivity for heavy metals due to stronger coordination interactions between metal ions and surface ligands (Kumar & Singh, 2021). This makes functionalized silica particularly attractive for targeted removal of specific ions (e.g., Pb^{2+}) in complex aqueous systems.

Key properties: surface area, porosity, active sites

Across these categories, adsorption performance is mainly governed by:

- **Surface area and porosity**, which determine how many sites are accessible and how quickly pollutants can diffuse to the surface.
- **Active sites** (exchangeable ions, hydroxyl groups, ligand groups), which control binding strength and selectivity.

- **Surface charge behavior**, which changes with pH and influences electrostatic attraction/repulsion. Because these properties can be engineered through modification, many recent studies emphasize designing inorganic adsorbents with controlled pore architectures and chemically functional surfaces for higher efficiency and better real-water performance (Wang & Chen, 2009; Kumar & Singh, 2021).

3. ADSORPTION MECHANISMS

Adsorption by inorganic materials is not a single mechanism; rather, it is typically a combination of physicochemical interactions. Understanding dominant mechanisms is essential for selecting the right adsorbent and optimizing conditions such as pH, dose, and contact time.

Ion exchange

Ion exchange is especially important for zeolites and aluminosilicate materials. Metal ions in solution replace exchangeable cations (e.g., Na^+, K^+, Ca^{2+}) within the adsorbent structure. This mechanism is effective for many divalent metals but can be limited by competition from abundant ions in real wastewater (Kılıç et al., 2017).

Electrostatic attraction

Electrostatic interactions occur when charged pollutant species are attracted to oppositely charged adsorbent surfaces. Many oxide surfaces become positively or negatively charged depending on pH, meaning adsorption can change sharply across pH ranges. Electrostatic effects often contribute strongly at the early stages of adsorption due to fast surface interactions (Wang & Chen, 2009).

Surface complexation and coordination

Surface complexation refers to the formation of stronger, more specific bonds between pollutants and surface functional groups (e.g., –OH on oxides, $-NH_2$ on functionalized silica). This mechanism is commonly linked to higher selectivity and is often consistent with kinetic models suggesting chemically controlled adsorption (Kumar & Singh, 2021). In practice, functionalization is used precisely to increase the proportion of adsorption that occurs through these stronger interactions.

Redox and oxidation mechanisms (especially MnO_2)

Some inorganic adsorbents—particularly MnO_2-based systems—may support oxidation-related processes alongside adsorption. This can be relevant for certain inorganic species and organic dyes, where oxidation can transform pollutants into less harmful or more easily removable forms. Such combined behavior can increase overall removal efficiency compared with purely physical adsorption (Wang & Chen, 2009).

Factors controlling selectivity (pH, ionic strength, competing ions)

Selectivity and capacity are strongly affected by water chemistry:

- **pH** controls metal speciation in solution and surface charge of adsorbents.
- **Ionic strength** can compress the electrical double layer, reducing electrostatic attraction and changing adsorption efficiency.
- **Competing ions** (e.g., Ca^{2+}, Mg^{2+}, Na^+) can occupy sites and reduce uptake of target metals, especially in ion-exchange systems (Kılıç et al., 2017).

Because of these effects, adsorption studies often pair mechanistic discussion with isotherm and kinetic modeling to interpret how and why adsorption occurs under specific conditions (Foo & Hameed, 2010).

4. SURFACE MODIFICATION AND FUNCTIONALIZATION

Although many inorganic adsorbents already show good stability and baseline adsorption performance, their raw forms often have limitations such as low selectivity in complex wastewater, slow adsorption kinetics, or reduced capacity under competing-ion conditions. For this reason, **surface modification** has become one of the most effective strategies for improving both adsorption efficiency and real-world applicability. In general, modification aims to (i) increase the number of active sites, (ii) strengthen the binding interactions with target pollutants, and (iii) improve performance stability across a wider pH and ionic-strength range (Kumar & Singh, 2021; Wang & Chen, 2009).

Why modify: higher capacity and selectivity

The main motivation for modifying inorganic adsorbents is to achieve **higher adsorption capacity** and **greater selectivity** toward specific pollutants, especially heavy metal ions. In natural or unmodified adsorbents, binding may rely mostly on ion exchange or weak electrostatic attraction, which can be strongly affected by competing ions. Functionalization introduces stronger and more specific interactions (e.g., coordination bonding), which helps the adsorbent target certain metals even in multi-component solutions (Kumar & Singh, 2021). In addition, modification may increase surface roughness, improve pore accessibility, and enhance overall adsorption kinetics.

Nano-oxide loading, functional groups, and composite materials

Several modification routes are widely reported in the literature:

(a) Nano-oxide loading:

Silica or zeolite surfaces may be loaded with nanoparticles (e.g., Fe_2O_3, MnO_2) to increase the density of reactive sites and improve adsorption capacity. Nanoparticles often provide high surface energy and abundant hydroxyl groups, which promote metal binding through surface complexation (Wang & Chen, 2009).

(b) Functional group grafting (amine/thiol):

Functionalizing silica with **amine ($–NH_2$)** or **thiol ($–SH$)** groups is a well-established approach for strengthening metal uptake. Amine groups can coordinate with metal ions through lone-pair interactions, while thiol groups show strong affinity for certain soft metal ions. Such ligand-like interactions generally increase selectivity and help adsorption remain effective even when ionic competition is high (Kumar & Singh, 2021).

(c) Composite materials:

Hybrid composites combine the advantages of multiple components—for example, silica (high surface area and tunable porosity) with iron oxide (fast adsorption and easier separation), or zeolite-based composites designed for both ion exchange and complexation. Composites are often engineered to balance **high capacity**, **mechanical stability**, and **regeneration performance** (Wang & Chen, 2009).

Effects on performance and stability

Modification typically leads to measurable improvements in adsorption behavior. The most common observed outcomes include:

- **Increased adsorption capacity** due to added active sites and stronger binding.
- **Improved selectivity** resulting from functional groups tailored to target pollutants.
- **Enhanced kinetics** because modified surfaces often provide faster pollutant capture.
- **Greater stability and reusability**, particularly when the adsorbent is designed to maintain structure across pH changes and repeated regeneration cycles (Kumar & Singh, 2021).

However, modification must be optimized; excessive coating or pore blocking may reduce accessible surface area and lower adsorption efficiency. Therefore, successful design requires balancing surface chemistry enhancement with preservation of porosity and accessibility.

5. EXPERIMENTAL METHODOLOGY

To evaluate adsorption performance under controlled conditions, batch adsorption experiments are widely used because they are simple, reproducible, and suitable for comparing different adsorbent materials. Batch studies also support kinetic and isotherm modeling, which helps interpret the adsorption mechanism (Foo & Hameed, 2010).

Batch adsorption setup (dose, volume, time, agitation)

In a typical batch experiment, a pollutant solution is prepared (commonly 50–100 mL), and a measured adsorbent mass is added (e.g., 0.1–0.5 g). The mixture is stirred at a constant agitation speed (commonly 200–300 rpm) to ensure uniform contact between adsorbent and solution. Samples are collected over a defined contact-time range (e.g., 20–120 minutes) to evaluate adsorption kinetics and determine equilibrium time.

Operational parameters are carefully controlled because adsorption is sensitive to:

- **pH**, which affects both surface charge and metal speciation,
- **initial concentration**, which influences the driving force for adsorption,
- **adsorbent dose**, which determines site availability, and
- **temperature and ionic strength**, which can alter binding behavior.

Analytical methods (UV–Vis, AAS)

After sampling, solid–liquid separation is commonly achieved by centrifugation and filtration. The remaining pollutant concentration is then measured using:

- **UV–Vis spectrophotometry**, often used for dyes or metal complexes, and
- **Atomic absorption spectrometry (AAS)**, widely used for accurate quantification of metal ions in solution.

Calculations: removal % and adsorption capacity (mg/g)

Two core indicators are typically calculated:

1. **Removal efficiency (%)**

$$\text{Removal \%} = \frac{C_0 - C_t}{C_0} \times 100$$

where $C_0$is the initial concentration and $C_t$is the concentration at time t(or at equilibrium).

2. **Adsorption capacity (mg/g)**

$$q_t = \frac{(C_0 - C_t)\,V}{m}$$

where $q_t$is adsorption capacity at time t, $V$is solution volume (L), and $m$is adsorbent mass (g). At equilibrium, $q_e$is calculated using $C_e$instead of C_t. These values are then used for isotherm and kinetic fitting, commonly Langmuir/Freundlich and pseudo-order kinetic models (Foo & Hameed, 2010).

6. PERFORMANCE COMPARISON OF SELECTED ADSORBENTS

Comparative evaluation of inorganic adsorbents helps identify which materials are most suitable for practical application under different conditions. In this article, four representative adsorbents are considered: Fe_2O_3 nanoparticles, MnO_2 nanoparticles, amine-modified silica, and clinoptilolite zeolite. Their performance differences are largely explained by variations in surface area, functional groups, and dominant adsorption mechanisms (Wang & Chen, 2009; Kılıç et al., 2017).

Fe_2O_3 nanoparticles

Fe_2O_3 nanoparticles show rapid adsorption due to reactive surface hydroxyl groups and strong surface complexation behavior. They are often considered practically advantageous because iron oxide systems may be easier to separate and regenerate in applied settings (Wang & Chen, 2009). Modification typically increases performance further by enhancing active-site availability.

MnO_2 nanoparticles

MnO_2 nanoparticles can remove contaminants through a combination of adsorption and oxidation-related processes, making them useful not only for metal uptake but also for certain organic dyes. Their performance is often stable across moderate pH ranges, though the dominant mechanism may shift depending on solution chemistry (Wang & Chen, 2009).

Amine-modified silica

Amine-functionalized silica typically demonstrates high selectivity for heavy metals because $-NH_2$ groups can coordinate strongly with metal ions. Its large surface area and tunable porosity enhance capacity, and functionalization reduces the influence of competing ions in complex waters (Kumar & Singh, 2021).

Zeolite (clinoptilolite)

Clinoptilolite is valued as an economical and chemically stable natural adsorbent. Its main mechanism is ion exchange. While its capacity may be lower than engineered nanomaterials, zeolite remains attractive for low-cost applications and large-scale treatment because it is widely available and durable (Kılıç et al., 2017).

Comparative table (example summary)

Adsorbent	Surface area (m^2/g)	Optimal pH	Max capacity (mg/g)	Basic mechanism	Note
Fe_2O_3 nanoparticles	65–90	5–6	70–120	Complexation, electrostatic attraction	Improves with modification
MnO_2 nanoparticles	40–60	4–5	55–85	Oxidation + ion exchange	Also effective for dyes
Amine-modified silica	150–250	5–7	90–150	Surface coordination ($-NH_2$)	High Pb^{2+} selectivity
Zeolite (clinoptilolite)	20–40	3–6	25–40	Ion exchange	Natural, low-cost

7. ISOTHERM AND KINETIC MODELING

Modeling is essential in adsorption studies because it helps explain **how pollutants interact with adsorbent surfaces** and which mechanism dominates the process. In practice, equilibrium data are commonly interpreted using adsorption isotherms, while time-dependent data are evaluated using kinetic models. These models do not only "fit curves"; they also provide insight into whether adsorption is likely controlled by surface chemistry, diffusion, heterogeneous site distribution, or monolayer formation (Foo & Hameed, 2010).

Langmuir vs. Freundlich interpretation

The **Langmuir isotherm** assumes adsorption occurs on a homogeneous surface with a finite number of identical sites, leading to **monolayer adsorption**. When experimental data fit Langmuir well, it suggests that adsorption tends toward a saturated monolayer and that binding sites have relatively uniform energy. In many studies, engineered adsorbents such as functionalized silica or certain metal oxides often show Langmuir-type behavior because functional groups and active sites are designed to be consistent and highly reactive.

In contrast, the **Freundlich isotherm** is an empirical model that describes adsorption on **heterogeneous surfaces** with different site energies and possible multilayer behavior. Natural zeolites and less-uniform adsorbents frequently fit Freundlich more closely because their surfaces contain multiple adsorption environments. A Freundlich fit typically suggests that adsorption is influenced by site diversity and non-uniform pore structure, which is common in naturally occurring minerals (Foo & Hameed, 2010).

Pseudo-first-order vs. pseudo-second-order kinetics

Kinetic models describe how quickly adsorption occurs and what controls the rate. The **pseudo-first-order (PFO)** model often implies that adsorption rate is related to physical interaction and diffusion toward available sites, especially during early stages. However, in many heavy-metal adsorption systems, PFO may not fully describe the entire adsorption period.

The **pseudo-second-order (PSO)** model is frequently associated with **chemically controlled adsorption**, where the rate depends on interactions such as surface complexation or coordination. When PSO provides the best fit, it suggests that chemical bonding mechanisms—rather than only mass transfer—play a dominant role. For materials such as amine-functionalized silica and reactive metal oxides, PSO fitting is common because metal capture often involves stronger binding at active sites (Foo & Hameed, 2010).

What model fits imply about adsorption nature

Overall, model fitting helps interpret adsorption as either:

- **Monolayer vs. heterogeneous adsorption** (Langmuir vs. Freundlich), and
- **Physical/diffusion influence vs. chemical interaction dominance** (PFO vs. PSO).

In many comparative studies, **modified inorganic adsorbents** tend to show Langmuir and PSO behavior more often than raw minerals, reflecting the role of engineered active sites and stronger pollutant–surface interactions. This provides quantitative evidence for why surface modification is a key strategy for improving performance (Foo & Hameed, 2010).

8. REGENERATION AND REUSABILITY

From an industrial viewpoint, an adsorbent is valuable only if it is not "single-use." Therefore, regeneration and reuse are essential for reducing operational cost and minimizing secondary waste. Inorganic adsorbents are generally favorable in this regard because they often retain structural stability under harsh chemical regeneration conditions (Suresh & Tiwari, 2018).

Desorption agents and cycle testing (NaOH/HCl)

A common regeneration approach is **chemical desorption** using acids or bases. For example, **HCl** can protonate surface sites and release adsorbed metal ions, while **NaOH** can disrupt surface binding depending on the adsorption chemistry and metal species. After desorption, the adsorbent is washed, dried (if needed), and reused for the next cycle. Cycle testing typically evaluates adsorption performance over 3–5 cycles as a basic indicator of practical reusability.

Performance retention across cycles

In many laboratory studies, good adsorbents retain a high proportion of their original capacity after repeated cycles. Moderate performance loss can occur due to partial site blockage, surface alteration, or incomplete desorption, but strong inorganic frameworks—especially silica-based and oxide-based systems—often remain functional across multiple regeneration rounds (Suresh & Tiwari, 2018). Maintaining stable performance across cycles is particularly important for real wastewater, where organic matter and competing ions may gradually foul the adsorbent surface.

Practical implications for cost and sustainability

Regeneration directly improves **economic feasibility** because it reduces the amount of fresh adsorbent required. It also supports **environmental sustainability** by lowering solid waste generation. Therefore, the ability to regenerate inorganic adsorbents with simple acids or bases, while maintaining acceptable efficiency, is a major advantage of these materials compared with some organic sorbents that degrade or lose structure more rapidly (Suresh & Tiwari, 2018).

9. APPLICATIONS AND PRACTICAL CONSIDERATIONS

Heavy metals (Pb^{2+}, Cd^{2+}, Cr species)

Heavy metals are priority pollutants because they persist in the environment and are toxic at low concentrations. Adsorption is widely used for Pb^{2+}, Cd^{2+}, and chromium species removal, and inorganic nanomaterials are often reported to provide high adsorption capacities due to their reactive surfaces and tunable chemistry (Wang & Chen, 2009). Functionalized silica can offer higher selectivity, while zeolites provide an economical option where large-scale treatment is needed.

Organic dyes

Many industrial dyes are stable, visually polluting, and difficult to remove using conventional methods. Metal oxides (especially MnO_2-based systems) can be effective because they may offer both adsorption and oxidation-related removal pathways. Silica-based composites and modified oxides are also reported to bind dye molecules efficiently, depending on surface charge and functional groups.

Scaling issues: real wastewater complexity and mixtures

A major limitation of laboratory results is that they often involve single-solute solutions under controlled conditions. In real wastewater, multiple contaminants compete for adsorption sites, ionic strength is higher, and organic matter may foul surfaces. These factors can significantly reduce adsorption capacity compared with ideal lab conditions. Therefore, scaling up requires testing in **multi-component systems**, evaluating long-term regeneration under realistic conditions, and designing adsorbents that remain selective and stable in complex matrices (Suresh & Tiwari, 2018; Wang & Chen, 2009).

10. CONCLUSION

This article highlights that inorganic adsorbents—particularly metal oxide nanoparticles, amine-functionalized silica, and natural zeolites—remain among the most practical and effective materials for removing pollutants from water due to their chemical stability, structural durability, and regeneration potential. Comparative evaluation suggests that amine-modified silica typically provides the highest selectivity and capacity for heavy metals because coordination sites strongly bind target ions. Fe_2O_3 nanoparticles often combine strong adsorption with practical handling and separation advantages, while MnO_2 nanoparticles offer stable performance and can be especially useful in dye-related applications. Clinoptilolite zeolite, although lower in capacity, remains valuable as a low-cost and environmentally sustainable option for large-scale use (Wang & Chen, 2009).

Most importantly, the evidence supports that surface modification is the main driver of improved performance. Functional groups, nano-oxide loading, and composite design increase active-site density, strengthen pollutant binding, and improve resistance to competing ions and repeated reuse. Future work should prioritize greener synthesis methods, improved selectivity in mixed-pollutant systems, and regeneration strategies that maintain performance under real wastewater conditions (Suresh & Tiwari, 2018).

References

Foo, K. Y., & Hameed, B. H. (2010). Insights into the modeling of adsorption isotherm systems. *Chemical Engineering Journal, 156*(1), 2–10. https://doi.org/10.1016/j.cej.2009.09.013

Kılıç, M., et al. (2017). Natural zeolites (clinoptilolite) for heavy metal removal from aqueous solutions: A review. *Journal of Cleaner Production, 168*, 1020–1034. https://doi.org/10.1016/j.jclepro.2017.09.066

Kumar, P., & Singh, M. (2021). *Functionalized nanomaterials as eco-friendly adsorbents for water treatment.* Elsevier.

Suresh, K., & Tiwari, A. (2018). *Nanomaterials for water remediation.* Springer. https://doi.org/10.1007/978-3-319-73793-0

Wang, J., & Chen, C. (2009). Adsorption of heavy metals by nanomaterials: A review. *Journal of Hazardous Materials, 170*(1), 1–12. https://doi.org/10.1016/j.jhazmat.2009.04.074

Nature Communications. (2024). *Fe_2O_3 nanoparticles for removal of heavy metals from aqueous solutions.* https://www.nature.com/articles/s41598-024-76285

MDPI Water. (2021). *Nanomaterial adsorbents for pollutant removal.* https://www.mdpi.com/2073-4441/13/19/2659

Journal of Morphology. (2024). *Studies on modified oxide adsorbents.* https://j-morphology.com/0044-4537

Received: 11.15.2025
Revised: 11.20.2025
Accepted: 12.10.2025
Published: 12.13.2025

Luminis Applied Science and Engineering
ISSN: 3030-1831
Vol 2, No 4, 2025

Investigation of the Chemical Basis of the Temperature- and Environment-Dependent Color Change of Cobalt(II) Ions

Nurcan Valizada
[1] Valizada, N. Master's Student in Inorganic Chemistry, Nakhchivan State University, Nakhchivan, Azerbaijan. Corresponding Author. Email: nurcanvalizada@gmail.com. ORCID: https://orcid.org/0009-0004-9588-807X
https://doi.org/10.69760/lumin.2025004007

Abstract; The temperature- and environment-dependent color change of cobalt(II) ions is a chemical process closely related to the structural characteristics and electronic behavior of the complexes they form. In aqueous media, the Co^{2+} ion predominantly forms the octahedral, pink-colored $[Co(H_2O)_6]^{2+}$ complex. In this complex, the d-electrons of the cobalt ion split into specific energy levels under the field effect created by the water ligands, and the wavelength of the absorbed light results in the appearance of the pink color. As the temperature increases, the detachment of water molecules from the complex becomes easier, and the chloride ions present in the system form the tetrahedral, blue-colored $[CoCl_4]^{2-}$ complex with Co^{2+}. Since the ligand field splitting in this complex differs from that in the octahedral one, the absorption spectrum also changes, and consequently the solution turns blue. The endothermic nature of the equilibrium causes the reaction to shift to the right with increasing temperature, favoring the formation of the blue complex. The ionic strength of the medium, particularly the concentration of Cl^-, significantly affects the rate and stability of this transition. In certain cases, pH may also influence the stability of the complexes. This color change is one of the remarkable processes that illustrates the fundamental principles of coordination chemistry and holds particular importance in the study of cobalt(II) ions.

***Keywords**: Cobalt(II) ions, temperature, environment, equilibrium, complex*

1. INTRODUCTION

Cobalt(II) ions exhibit pronounced and reversible color changes in response to variations in temperature and chemical environment, making them one of the most illustrative systems in coordination chemistry. Although this phenomenon is often introduced as a simple visual transformation, it reflects deeper processes involving coordination geometry, ligand substitution, electronic structure, and thermodynamic equilibrium. For this reason, cobalt(II) complexes are widely discussed in inorganic chemistry textbooks, laboratory demonstrations, and advanced research studies (Cotton et al., 1999; Housecroft & Sharpe, 2018).

In aqueous solution, Co^{2+} ions predominantly exist as the octahedral hexaaqua complex, $[\mathrm{Co(H_2O)_6}]^{2+}$, in which six water molecules symmetrically coordinate to the metal center. This complex is thermodynamically stable under ambient conditions and exhibits a characteristic pink color. The color arises from d–d electronic transitions governed by octahedral ligand field splitting, where the energy separation between the t_{2g} and e_g orbitals determines the wavelength of absorbed visible light (Cotton et al., 1999; Miessler & Fischer, 2014).

As the temperature increases, the Co–OH_2 bonds become weaker due to enhanced thermal motion, facilitating partial dissociation of coordinated water molecules. In chloride-rich environments, chloride ions readily replace water ligands and stabilize the tetrahedral tetrachlorocobaltate(II) complex, $[\mathrm{CoCl_4}]^{2-}$. This structural transformation from octahedral to tetrahedral coordination results in a distinct change in ligand field strength and geometry, leading to a blue coloration of the solution. The color shift from pink to blue is therefore a direct consequence of altered d-orbital splitting patterns in tetrahedral versus octahedral fields (Miessler & Fischer, 2014; Housecroft & Sharpe, 2018).

The equilibrium between $[\mathrm{Co(H_2O)_6}]^{2+}$and $[\mathrm{CoCl_4}]^{2-}$is endothermic in the forward direction, favoring the blue tetrahedral complex at elevated temperatures. Upon cooling, the equilibrium shifts back toward the pink octahedral species, demonstrating the reversible nature of the process. This behavior provides a clear and accessible example of Le Châtelier's principle and highlights the interplay between kinetic and thermodynamic factors in coordination reactions (Coordination Chemistry Reviews, 2016; Dalton Transactions, n.d.).

In addition to temperature, the composition of the surrounding medium strongly influences complex stability. Chloride ions act as stronger ligands than water molecules, enhancing the formation and persistence of the tetrahedral complex in chloride-rich solutions. Changes in ionic strength and, in some cases, pH can further modify ligand substitution equilibria and affect color intensity by promoting alternative cobalt(II) coordination species (Inorganica Chimica Acta, 2012). Spectroscopic investigations, particularly UV–Vis studies, have confirmed that these environmental changes lead to measurable shifts in absorption bands corresponding to altered electronic transitions (Spectrochimica Acta Part A, 2018).

Beyond its theoretical significance, the temperature- and environment-dependent color change of cobalt(II) ions has practical relevance. Such systems are employed in humidity indicators, thermochromic materials, and analytical sensors, where visible color variation provides a simple and effective means of monitoring environmental conditions. Consequently, cobalt(II) complexes serve as an important bridge between fundamental coordination chemistry and applied materials science.

Extensive literature supports this interpretation. Classical inorganic chemistry texts provide the theoretical foundation for understanding ligand field effects and coordination geometry (Cotton et al., 1999; Housecroft & Sharpe, 2018). Experimental laboratory studies demonstrate the reversible color transition under controlled temperature changes (Journal of Chemical Education, n.d.), while detailed kinetic and thermodynamic analyses elucidate ligand exchange mechanisms and stability constants of cobalt(II) complexes (Coordination Chemistry Reviews, 2016; Dalton Transactions, n.d.). Together, these studies establish the cobalt(II) color transition as a well-characterized yet continually relevant model system in coordination chemistry.

2. Structure and Electronic Behavior of Cobalt(II) Complexes

The cobalt(II) ion possesses a **d^7 electronic configuration**, which plays a decisive role in determining its spectroscopic and color properties in different coordination environments. In an **octahedral ligand field**, such as in the hexaaquacobalt(II) complex $[\mathrm{Co(H_2O)_6}]^{2+}$, the five d-orbitals split into two energy levels: the lower-energy t_{2g}set and the higher-energy $e_g$set. The magnitude of this crystal field splitting (Δ_o) governs the wavelength of light absorbed during d–d electronic transitions, giving rise to the characteristic **pink coloration** observed in aqueous cobalt(II) solutions (Cotton et al., 1999; Miessler & Fischer, 2014).

In contrast, when cobalt(II) adopts a **tetrahedral coordination geometry**, as in the $[\mathrm{CoCl_4}]^{2-}$complex, the splitting of the d-orbitals is reversed and significantly weaker. According to ligand field theory, tetrahedral crystal field splitting (Δ_t) is approximately four-ninths of the octahedral splitting, resulting in absorption of lower-energy (longer-wavelength) visible light. This shift in electronic transition energies produces the intense **blue color** characteristic of tetrahedral cobalt(II) complexes (Housecroft & Sharpe, 2018).

Therefore, the observed color change between pink and blue cobalt(II) complexes is fundamentally linked to **coordination geometry, ligand field strength, and d–d electronic transitions**. The ligand substitution from weak-field water molecules to stronger-field chloride ligands alters both the symmetry and electronic environment of the metal center, providing a clear visual manifestation of changes in electronic structure predicted by coordination chemistry theory (Cotton et al., 1999; Housecroft & Sharpe, 2018).

3. Effect of Temperature on Equilibrium

The interconversion between the octahedral $[\mathrm{Co(H_2O)_6}]^{2+}$complex and the tetrahedral $[\mathrm{CoCl_4}]^{2-}$complex represents a **thermodynamically controlled equilibrium** that is highly sensitive to temperature. This transformation is widely recognized as an **endothermic process**, meaning that increasing temperature favors the formation of the tetrahedral cobalt(II) species. As thermal energy increases, cobalt–water coordination bonds weaken, facilitating ligand dissociation and subsequent substitution by chloride ions (Miessler & Fischer, 2014).

Experimental laboratory investigations reported in the *Journal of Chemical Education* have demonstrated that within a temperature range of approximately **20–70 °C**, aqueous cobalt(II) chloride solutions gradually change color from pink to blue as temperature rises. This visible transition reflects the equilibrium shift toward the tetrahedral $[\mathrm{CoCl_4}]^{2-}$complex at higher temperatures (Journal of Chemical Education, n.d.). Upon cooling, the system reversibly returns to the pink octahedral form, confirming the dynamic and reversible nature of the process.

From a thermodynamic perspective, this temperature dependence is consistent with the **Van't Hoff relationship**, which predicts that the equilibrium constant for an endothermic reaction increases with temperature. Detailed kinetic and thermodynamic studies further show that ligand exchange rates and stability constants of cobalt(II) complexes vary significantly with temperature, influencing both the speed and extent of the color transition (Coordination Chemistry Reviews, 2016; Dalton Transactions, n.d.).

Thus, the temperature-driven color change of cobalt(II) complexes provides a classic and experimentally accessible demonstration of equilibrium thermodynamics in coordination chemistry, linking macroscopic observations directly to molecular-level structural and energetic changes.

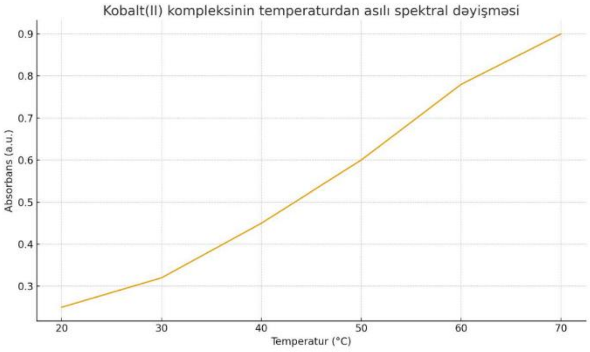

Figure 1. Illustration of the graph showing the increase in the fraction of the blue $[\mathrm{CoCl_4}]^{2-}$ complex with rising temperature

(The x-axis represents temperature, and the y-axis represents the relative amount of the complex; the graph exhibits an increasing trend.)

Thermodynamic studies (Coordination Chemistry Reviews, 2016) indicate that the enthalpy change of the transition is positive. This explains why, as the temperature increases, the equilibrium shifts to the right, favoring the formation of the $[CoCl_4]^{2-}$ complex.

3. Role of Chloride Ions in the Medium

The Cl^- ion acts as a ligand, creating a stronger interaction with the Co^{2+} ion. As the ionic strength increases or an electrolyte such as NaCl is added, the equilibrium shifts from the aqua-ligand complex to the chloride-ligand complex. According to *Inorganica Chimica Acta* (2012), when the Cl^- concentration increases from 0.1 M to 1 M, the formation constant of the $[CoCl_4]^{2-}$ complex rises sharply, resulting in a more intense blue color of the solution. (see Figure 2)

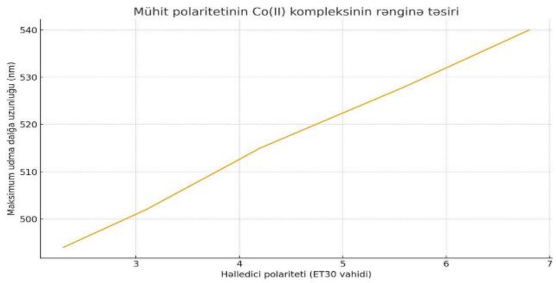

Figure 2. Illustration of the graph showing the increase in the fraction of the $[CoCl_4]^{2-}$ complex as the Cl^- concentration rises.

(The graph rises in a curved (non-linear) manner)

This phenomenon is confirmed from thermodynamic, kinetic, and spectroscopic perspectives.

4. Spectral Observations and Methods Used

The color change of Co^{2+} complexes is primarily studied using UV-Vis spectroscopy. *Spectrochimica Acta Part A* (2018) reports that as the temperature increases, the absorption bands shift toward longer wavelengths, indicating changes in the electronic structure of the complex.

Methods applicable to this study include:

1. **Recording UV-Vis spectra:** The absorption peaks of the solution are monitored at different temperatures.
2. **Thermostatted water bath:** Solutions are maintained at various temperatures, and color changes are recorded.
3. **Addition of Cl^- ions:** NaCl is added at different concentrations to observe shifts in equilibrium.
4. **Van't Hoff analysis:** ΔH and ΔS are calculated from the linear relationship between lnK and 1/T.
5. **Visual observation and photographic records:** The color transition is evaluated both spectroscopically and visually.

The application of these methods allows for both qualitative and quantitative analysis of complex behavior.

5. CALCULATION AND MODELING OF EQUILIBRIUM CONSTANTS

The Van't Hoff equation is given as:

$$\ln K = -\Delta H/RT + \Delta S/R$$

Coordination Chemistry Reviews (2016) indicates that this equilibrium corresponds to a typical endothermic process. As the temperature increases, the equilibrium constant K rises, which corresponds to an increased fraction of the blue $[CoCl_4]^{2-}$ complex. (see Figure 3)

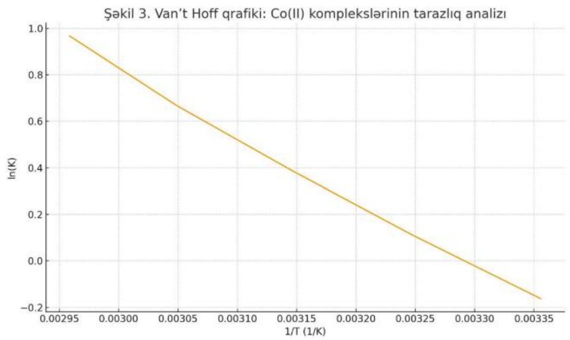

Figure 3. Illustration of the Van't Hoff plot.

(The natural logarithm of the equilibrium constant (ln K) is plotted on the y-axis, and the reciprocal of temperature (1/T) is on the x-axis; the line exhibits a negative slope.)

This result provides a complete thermodynamic explanation of the behavior of Co^{2+} complexes.

6. APPLICATIONS AND PRACTICAL SIGNIFICANCE

The temperature- and environment-dependent color change of cobalt(II) complexes is not only of theoretical importance but also has considerable **practical relevance**. One of the most widely known applications involves **cobalt(II) chloride–based materials**, which are commonly used in **humidity indicators** and **moisture-sensitive packaging systems**. In these applications, the reversible color transition between pink and blue provides a simple visual signal indicating changes in environmental humidity or temperature. As noted by Miessler and Fischer (2014), the sensitivity of the $[Co(H_2O)_6]^{2+} \leftrightarrow [CoCl_4]^{2-}$ equilibrium to external conditions makes cobalt(II) compounds particularly suitable for such indicator systems.

In addition, cobalt(II) complexes have been explored for use in **temperature sensors** and **thermochromic materials**, where controlled and reversible color variation is essential. Because the color transition is governed by well-defined thermodynamic parameters, cobalt-based systems can be calibrated to respond within specific temperature ranges, increasing their reliability and reproducibility. This property is especially valuable in analytical chemistry, where cobalt(II) complexes are employed in laboratory demonstrations and qualitative analysis to illustrate ligand substitution, equilibrium shifts, and coordination geometry changes under controlled conditions (Housecroft & Sharpe, 2018).

The durability and reversibility of cobalt(II) color transitions further enhance their applicability. Unlike irreversible chromic systems, cobalt-based indicators can undergo multiple heating–cooling or hydration–

dehydration cycles without significant loss of performance. This reusability reduces material costs and supports sustainable use in both industrial and laboratory settings. Consequently, cobalt(II) complexes represent a practical intersection of coordination chemistry principles and functional material design.

CONCLUSION

The present study demonstrates that the color transition of cobalt(II) ions in response to temperature and environmental changes is a scientifically rich and practically valuable phenomenon that vividly illustrates fundamental concepts of coordination chemistry. The reversible transformation between the octahedral, pink $[\mathrm{Co(H_2O)_6}]^{2+}$complex and the tetrahedral, blue $[\mathrm{CoCl_4}]^{2-}$complex clearly reflects the influence of coordination geometry, ligand field strength, and electronic structure on observable chemical properties. These transitions also provide direct evidence of the thermodynamic and kinetic principles governing ligand substitution equilibria.

The novelty of this work lies in its **integrated interpretation** of cobalt(II) color changes, combining electronic structure considerations, equilibrium thermodynamics, and environmental effects under realistic laboratory conditions. Rather than relying solely on idealized theoretical models, the analysis connects ligand field theory with experimentally observable behavior, offering a more comprehensive understanding of complex stability, ligand-binding strength, and equilibrium mechanisms.

From a practical perspective, the findings highlight the continued relevance of cobalt(II) complexes in applied chemistry. Their temperature- and environment-sensitive color transitions enable applications in **humidity indicators, thermochromic sensors, packaging safety systems, and analytical methodologies**. The reversible nature of these transitions ensures both sensitivity and reusability, making cobalt(II)-based materials attractive for long-term use.

In conclusion, the study of cobalt(II) ion color transitions remains important not only for advancing fundamental knowledge in coordination chemistry but also for supporting the development of functional materials and sensing technologies. Ongoing research in this field may lead to improved cobalt-based systems with enhanced stability, greater precision, and expanded applications in modern chemical science and materials engineering.

REFERENCES

Chenakin, S. P., Alekseev, S. A., & Kruse, N. (2022). X-ray photoelectron spectroscopy and diffuse reflectance infrared Fourier transform spectroscopy insight into the pathways of manganese oxalate thermal decomposition to MnO and MnCO3. *Inorganic Chemistry*, *61*(31), 12106-12117.

Cotton, F. A., Wilkinson, G., Murillo, C. A., & Bochmann, M. (1999). *Advanced inorganic chemistry* (6th ed.). John Wiley & Sons.

Effect of chloride ions on the stability of Co(II) complexes. (2012). *Inorganica Chimica Acta*.

Effect of temperature on the UV–Vis spectra of Co(II) complexes. (2018). *Spectrochimica Acta Part A: Molecular and Biomolecular Spectroscopy*.

Housecroft, C. E., & Sharpe, A. G. (2018). *Inorganic chemistry* (5th ed.). Pearson.

Hruska, E., Zhu, Q., Biswas, S., Fortunato, M. T., Broderick, D. R., Morales, C. M., ... & Baker, L. R. (2024). Water-Mediated Charge Transfer and Electron Localization in a Co3Fe2 Cyanide-Bridged Trigonal Bipyramidal Complex. *Journal of the American Chemical Society*, *146*(12), 8031-8042.

Investigation of kinetic and thermodynamic properties of Co(II) complexes. (n.d.). *Dalton Transactions*.

Laboratory studies on the effect of temperature on the color change of Co(II) complexes. (n.d.). *Journal of Chemical Education*.

Miessler, G. L., & Fischer, P. J. (2014). *Inorganic chemistry* (5th ed.). Pearson.

Review on thermodynamic parameters and ligand exchange mechanisms of Co(II) complexes. (2016). *Coordination Chemistry Reviews*.

Trouillas, P., Sancho-García, J. C., De Freitas, V., Gierschner, J., Otyepka, M., & Dangles, O. (2016). Stabilizing and modulating color by copigmentation: Insights from theory and experiment. *Chemical reviews*, *116*(9), 4937-4982.

Zhang, X., Xu, J., Guo, Z., & Gong, M. (2017). Luminescence and energy transfer of dual-emitting solid solution phosphors (Ca, Sr) 10Li (PO4) 7: Ce3+, Mn2+ for ratiometric temperature sensing. *Industrial & Engineering Chemistry Research*, *56*(4), 890-898.

Received: 11.15.2025
Revised: 11.20.2025
Accepted: 12.10.2025
Published: 12.13.2025

Luminis Applied Science and Engineering

Editor-in-Chief: Maftun Ismayil oghlu Ismayilov
Executive Secretary: Gerda Urbaite
Salomėjos Nėries g. 57, Vilnius, Lithuania
E-mail: editor@egarp.lt

Vol. 2 No. 4 (2025):

ISSN 3030-1831

Luminis Applied Science and Engineering (LUMIN) ***(ISSN: 3030-1831)*** is an open-access, peer-reviewed journal dedicated to publishing high-quality research, reviews, and case studies in applied science, engineering, informatics, and computing. Committed to illuminating advanced research and practical innovations, LUMIN serves as a platform for interdisciplinary exploration and technological advancements that address complex global challenges.

Focus and Scope

Luminis Applied Science and Engineering publishes original research and insights across a diverse range of topics, including:

- Applied Science and Engineering Solutions
- Emerging Technologies and Innovation
- Sustainable Energy and Environmental Engineering
- Advanced Materials and Nanotechnology
- Artificial Intelligence and Machine Learning
- Robotics and Automation
- Informatics and Data Science
- Computing and Computational Engineering
- Cybersecurity and Information Technology
- Interdisciplinary Research in Applied Science and Technology

The journal is dedicated to fostering collaboration across scientific disciplines and encourages submissions from researchers, practitioners, and academics seeking to advance both theoretical and practical applications in their fields.

Open Access Policy

As an open-access journal, *LUMIN* provides unrestricted access to all published content, ensuring that knowledge is freely available to the global research community. This aligns with our mission to promote knowledge dissemination and to support researchers by removing access barriers.

Copyright and Archiving

All articles published in *LUMIN* are licensed under a [Creative Commons Attribution License], allowing readers to share and adapt the work with appropriate credit to the authors. The journal is committed to long-term digital preservation and is included in the CLOCKSS and LOCKSS archival systems to safeguard its contents.

Submission and Peer Review

Luminis Applied Science and Engineering operates a rigorous, double-blind peer review process to uphold academic standards and ensure the publication of reliable and impactful research. We encourage researchers worldwide to contribute their original findings and to actively participate in the peer-review process.

Published quarterly, *LUMIN* ensures that accepted articles are made available online promptly, offering rapid publication and maximum visibility for authors' work.

Luminis Applied Science and Engineering
Editor-in-Chief: Maftun Ismayil oghlu Ismayilov
Executive Secretary: Gerda Urbaite
Salomėjos Nėries g. 57, Vilnius, Lithuania
E-mail: editor@egarp.lt