Metal and Graphene-Based Nanohybrids for Electrochemical Detection and Remediation of Environmental Pesticides: A Critical Review

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doi.org/10.64643/IJIRTV12I8-189939-459

Abstract— **Environmental contamination by pesticides has emerged as one of the most severe ecological and human-health concerns. Conventional methods for pesticide detection and remediation are often time-consuming, costly, and lack sensitivity. Recent advances in nanotechnology particularly the synthesis of metal and grapheme based nano hybrids have enabled the design of efficient, cost-effective, and highly selective electrochemical sensors and catalytic materials. This review provides a comprehensive overview of current progress in the development of grapheme metal nano composites for pesticide sensing and environmental detoxification. Emphasis is placed on the synthesis techniques, physicochemical properties, electrochemical behaviour, and synergistic effects of these nanohybrids. The mechanisms of detection and degradation, performance parameters, and limitations are critically discussed. The review concludes with future perspectives for sustainable remediation strategies and potential integration into portable sensor devices.**

Index Terms— **Graphene, Nanohybrids, Environmental remediation, Sensors, Catalysis**

I. INTRODUCTION

The extensive and often indiscriminate use of pesticides in modern agriculture has resulted in pervasive contamination of environmental matrices, including soil, surface and groundwater, and food chains. Residual pesticides and their transformation products are now recognized as major contributors to ecological imbalance and public health risks, causing neurotoxicity, endocrine disruption, carcinogenic effects, and loss of biodiversity [1,2]. The increasing regulatory emphasis on food safety, environmental monitoring, and sustainable agriculture has intensified the demand for sensitive, rapid, and field-deployable analytical technologies for pesticide surveillance.

Conventional analytical techniques such as gas chromatography (GC), high-performance liquid chromatography (HPLC), and mass spectrometry (MS) remain the gold standards for pesticide analysis due to their high accuracy and reliability [3]. However, these methods are inherently limited by complex sample preparation, high operational costs, bulky instrumentation, and the requirement for skilled personnel, rendering them unsuitable for real-time and on-site monitoring. Consequently, alternative sensing strategies that combine sensitivity, portability, and cost-effectiveness are urgently needed.

Electrochemical sensing has emerged as a promising platform for pesticide detection owing to its rapid response, low detection limits, operational simplicity, and compatibility with miniaturized and portable devices [4]. The analytical performance of electrochemical sensors is strongly governed by the nature of the electrode materials, which directly influence electron transfer kinetics, adsorption behavior, and catalytic activity toward pesticide molecules. In this context, graphene and its derivatives have attracted considerable attention due to their exceptional electrical conductivity, high specific surface area, mechanical robustness, and chemical stability. Nevertheless, pristine graphene often exhibits limited intrinsic catalytic activity and insufficient selectivity, which can compromise its sensing performance for complex environmental samples.

To address these challenges, graphene-based nanohybrids incorporating metal and metal oxide nanoparticles such as Au, Ag, Pt, CuO, ZnO, and

Fe_3O_4 have been extensively developed. These metal–graphene nanohybrids exploit synergistic interactions between graphene's superior electron mobility and the catalytic properties of metal species, resulting in enhanced charge transfer, increased electroactive surface area, and improved sensitivity and selectivity toward a wide range of pesticide classes [5,6]. Beyond sensing, such hybrids have also demonstrated potential in electrochemical and catalytic remediation, enabling the degradation or adsorption of pesticide residues and thus offering dual-function platforms for environmental monitoring and pollutant mitigation.

Despite significant progress, several critical challenges hinder the translation of metal–graphene nanohybrids from laboratory studies to real-world applications. Issues such as nanoparticle aggregation, metal leaching, long-term stability, reproducibility, scalability of synthesis, and potential ecotoxicological impacts remain inadequately addressed [7,8]. Furthermore, most reported studies are confined to controlled laboratory conditions, with limited validation in complex environmental matrices or field settings.

This critical review systematically evaluates recent advances in metal- and graphene-based nanohybrids for the electrochemical detection and remediation of environmental pesticides, drawing upon verified literature published between 2012 and 2025. Emphasis is placed on structure–property–performance relationships, sensing mechanisms, remediation pathways, and comparative performance across different hybrid systems. Current limitations, knowledge gaps, and regulatory considerations are critically discussed, and future research directions toward sustainable, scalable, and environmentally safe nanohybrid technologies are proposed.

II. SYNTHESIS STRATEGIES FOR METAL–GRAPHENE NANOHYBRIDS

The synthesis of metal–graphene nanohybrids plays a pivotal role in determining their structural integrity, interfacial chemistry, and electrochemical performance. Reported fabrication strategies are broadly classified into in situ and ex situ approaches, encompassing chemical reduction, hydrothermal/solvothermal processing, sol–gel techniques, electrodeposition, photochemical methods, and environmentally benign green synthesis routes [9,10]. The choice of synthesis methodology directly governs metal nanoparticle dispersion, metal–graphene interfacial bonding, electronic coupling, and catalytic activity, thereby influencing both sensing sensitivity and remediation efficiency.

2.1 In Situ Chemical Reduction Methods

Chemical reduction remains the most extensively reported route for fabricating noble metal– and transition metal–graphene nanohybrids. In a typical in situ process, graphene oxide (GO) is dispersed in aqueous or alcoholic media containing metal precursors such as $HAuCl_4$, $AgNO_3$, $PtCl_6^{2-}$, or $Cu(NO_3)_2$. Chemical reducing agents including sodium borohydride, hydrazine hydrate, or ascorbic acid are subsequently introduced to simultaneously reduce metal ions and GO to reduced graphene oxide (rGO). The oxygen-containing functional groups on GO act as nucleation sites, enabling uniform anchoring of metal nanoparticles and preventing agglomeration. For instance, Au nanoparticles synthesized via in situ reduction exhibit homogeneous dispersion on rGO sheets, resulting in enhanced electron transfer and improved sensitivity toward organophosphate and carbamate pesticides [11].

2.2 Sol–Gel and Metal Oxide Integration Routes

Sol–gel techniques are frequently employed for incorporating metal oxides such as TiO_2, CeO_2, ZnO, and CuO into graphene matrices. In this approach, metal alkoxides or metal salts undergo hydrolysis and condensation reactions in the presence of GO, leading to the formation of oxide nanostructures intimately coupled with graphene sheets. These hybrids exhibit modulated band structures, increased surface defect density, and abundant catalytic active sites. TiO_2–graphene and CeO_2–graphene nanohybrids synthesized via sol–gel routes have demonstrated improved photoelectrochemical and electrochemical responses, particularly for pesticides requiring oxidative degradation pathways [12,13].

2.3 Solvothermal and Hydrothermal Synthesis

Hydrothermal and solvothermal methods utilize elevated temperature and pressure within sealed autoclaves to promote controlled nucleation and crystal growth of metal or metal oxide nanoparticles on graphene surfaces. These techniques are particularly advantageous for synthesizing crystalline metal oxide–graphene hybrids such as Fe_3O_4/rGO, ZnO/rGO, and NiO/Rgo [14-16]. Under hydrothermal conditions, GO is partially or fully reduced, while strong interfacial bonding between graphene and metal oxides is established. Magnetic Fe_3O_4–graphene hybrids fabricated through this route have attracted significant attention for pesticide remediation due to their combined sensing capability and facile magnetic recovery [17-18].

2.4 Electrodeposition-Based Fabrication

Electrodeposition offers a highly controllable and reproducible strategy for fabricating metal–graphene nanohybrids directly on conductive substrates. In this approach, graphene-modified electrodes are immersed in metal-ion-containing electrolytes, and metal nanoparticles are deposited under potentiostatic or galvanostatic conditions. Parameters such as deposition potential, time, and electrolyte composition allow precise control over nanoparticle size, loading density, and morphology [19-21]. Noble metal–graphene hybrids synthesized via electrodeposition exhibit excellent electrical connectivity and mechanical stability, making them particularly suitable for electrochemical sensor platforms targeting trace-level pesticide detection.

2.5 Photochemical Reduction Methods

Photochemical synthesis utilizes ultraviolet or visible light irradiation to induce the reduction of metal ions in the presence of graphene or GO, eliminating the need for strong chemical reductants. In this process, photo excited electrons generated within graphene or semiconductor components reduce metal precursors, resulting in well-dispersed nanoparticles [22-24]. Photochemically synthesized metal–graphene hybrids often exhibit clean surfaces and enhanced catalytic activity, which are advantageous for both electrochemical sensing and photocatalytic degradation of pesticide residues.

2.6 Green and Eco-Friendly Synthesis Approaches

In response to growing sustainability concerns, green synthesis strategies employing plant extracts, biopolymers, and other natural reductants have gained increasing attention. Phytochemicals such as polyphenols, flavonoids, and sugars act as both reducing and stabilizing agents, facilitating the formation of metal–graphene nanohybrids under mild conditions [25]. Green-synthesized Ag–graphene, Au–graphene, and metal oxide–graphene systems have demonstrated promising electrochemical performance while minimizing environmental and toxicological risks [26-27]. However, variability in precursor composition and particle size distribution remains a challenge for large-scale reproducibility.

2.7 Ex Situ Assembly and Hybridization

In ex situ methods, pre-synthesized metal or metal oxide nanoparticles are physically or chemically assembled onto graphene or rGO sheets through electrostatic attraction, π–π interactions, or covalent bonding. Although this approach offers independent control over nanoparticle properties, weaker interfacial interactions may limit long-term stability and electron transfer efficiency compared to in situ strategies [28-29]. Nevertheless, ex situ assembly remains valuable for constructing complex multicomponent and bimetallic hybrid architectures.

2.8 Comparative Considerations for Sensor and Remediation Design

The selection of a synthesis strategy is dictated by the target pesticide, required detection limits, operational environment, and intended application (sensing versus remediation). Noble metal–graphene hybrids synthesized via chemical reduction or electro deposition typically provide superior sensitivity and selectivity, whereas metal oxide–graphene hybrids fabricated through hydrothermal or sol–gel routes offer multi functionality and cost-effectiveness [30-31]. Green synthesis approaches align with sustainable environmental monitoring but require further optimization for reproducibility and long-term stability.

Table 1. Summary of Synthesis Routes for Metal–Graphene Nanohybrids

Synthesis Route	Representative Metal / Metal Oxide Types	Graphene Form	Key Structural Features	Primary Applications
In situ chemical reduction	Au, Ag, Pt, Pd, Cu	GO, rGO	Uniform nanoparticle dispersion; strong metal–graphene coupling; high conductivity	Electrochemical sensing of organophosphate, carbamate, and organochlorine pesticides
Ex situ assembly	Au, Ag, Cu, Fe_3O_4	rGO	Independent control of particle size; weaker interfacial bonding	Multi-component sensors; proof-of-concept sensing platforms
Hydrothermal synthesis	Fe_3O_4, ZnO, NiO, Co_3O_4, MnO_2	GO, rGO	Crystalline oxide phases; strong interfacial bonding; hierarchical morphology	Dual-function sensing and remediation; magnetic separation-assisted pesticide removal
Solvothermal synthesis	CuO, ZnO, TiO_2, CeO_2	rGO	Controlled particle growth; high crystallinity; defect-rich graphene	Electrochemical sensing and catalytic degradation of pesticides
Sol–gel method	TiO_2, CeO_2, ZnO, SnO_2	GO	Tunable bandgap; high density of surface-active sites	Photo electrochemical sensing; oxidative degradation of persistent pesticides
Electro deposition	Au, Ag, Pt, Cu, Ni	Graphene-coated electrodes	Precise control over nanoparticle size and loading; excellent electrical contact	High-sensitivity electrochemical sensors; portable and on-site detection devices
Photochemical reduction	Au, Ag, Pt	GO, rGO	Clean nanoparticle surfaces; minimal chemical residues	Electrochemical sensing; photo catalytic pesticide degradation
Green / bio-inspired synthesis	Ag, Au, Fe_3O_4, ZnO	GO, rGO	Eco-friendly fabrication; biogenic capping agents	Sustainable sensors; environmental monitoring and remediation
Bimetallic co-reduction	Au–Pt, Ag–Cu, Pd–Ni	rGO	Synergistic catalytic effects; enhanced charge transfer	Ultra-sensitive sensing; multi-pesticide detection
Doped graphene–metal hybrids	Au/N-rGO, Fe_3O_4/N-rGO	Doped graphene	Increased defect density; improved selectivity	Selective electrochemical sensing in complex matrices

III. ELECTROCHEMICAL DETECTION OF PESTICIDES

Electrochemical techniques have emerged as powerful analytical tools for pesticide detection due to their inherent advantages of high sensitivity, rapid response, low operational cost, and compatibility with portable and in situ monitoring devices. Commonly employed electrochemical methods include cyclic voltammetry (CV), differential pulse voltammetry (DPV), square wave voltammetry (SWV), and amperometry, each offering distinct advantages depending on the redox behaviour and adsorption characteristics of target pesticide molecules [32-35]. The electrochemical response is governed by the interfacial interactions between pesticide molecules and the electrode surface, which are strongly influenced by the physicochemical properties of the sensing material.

3.1 Graphene-Based Nano materials in Pesticide Detection

Graphene and its derivatives such as graphene oxide (GO), reduced graphene oxide (rGO), and heteroatom-doped graphene have been extensively explored as electrochemical sensing platforms for pesticide detection. The superior electrical conductivity, high surface area, and two-dimensional structure of graphene facilitate rapid electron transfer and increased adsorption of pesticide molecules.

Graphene-based sensors primarily operate through adsorption-controlled electrochemical processes. Pesticide molecules interact with graphene surfaces via π–π stacking, electrostatic attraction, and hydrogen bonding, particularly in GO and doped graphene systems containing oxygen or heteroatom functional groups. Upon adsorption, the electroactive pesticide undergoes oxidation or reduction at characteristic potentials, generating a measurable current response.

For non-electro active pesticides, indirect detection mechanisms involving enzymatic inhibition or mediator-based signal transduction are often employed [36-39].

The high density of edge defects and surface functional groups in graphene derivatives enhances electron tunnelling and facilitates charge transfer at the electrode–electrolyte interface. However, pristine graphene exhibits limited intrinsic catalytic activity, often leading to higher over potentials and moderate sensitivity. Doping graphene with nitrogen, sulphur, or boron increases defect density and alters electronic structure, thereby improving electro catalytic performance and selectivity.

3.2 Metal-Based Nano materials in Pesticide Detection

Metal and metal oxide nanomaterials including Au, Ag, Pt, Cu, ZnO, TiO_2, and Fe_3O_4 are widely employed in electrochemical pesticide sensors due to their excellent catalytic activity and redox mediation capabilities [40-42].

Metal-based nanomaterials enhance electrochemical detection through catalytic oxidation or reduction of pesticide molecules at lower overpotentials. Noble metals such as Au and Pt facilitate direct electron transfer by providing active catalytic sites, while transition metal oxides participate in surface redox reactions and oxygen-vacancy-mediated charge transport. In certain systems, metal nanoparticles also act as electron mediators, accelerating charge transfer between the pesticide and the electrode surface.

The catalytic activity of metal-based nanomaterials arises from their high surface energy, exposed crystal facets, and variable oxidation states. Metal oxides, in particular, exhibit strong adsorption affinity toward pesticide functional groups, enabling preconcentration effects. However, issues such as nanoparticle agglomeration, surface fouling, and metal leaching can compromise long-term stability and reproducibility.

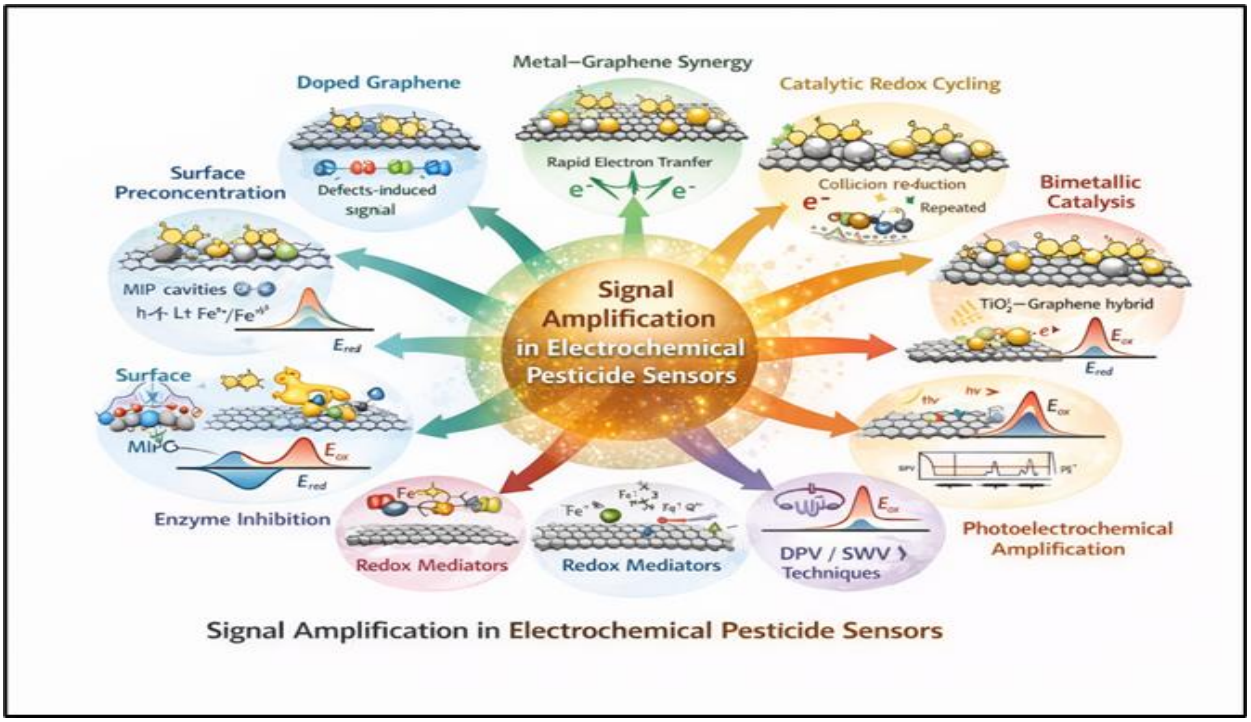

Fig 1: Signal amplification in electrochemical Pesticide sensors

Signal amplification strategies play a crucial role in achieving ultra-sensitive electrochemical detection of pesticides, particularly at trace and regulatory-relevant concentrations. These strategies rely on enhancing electron transfer efficiency, increasing the number of electroactive events per analyte molecule, or preconcentrating pesticide molecules at the electrode surface. Graphene-based materials amplify signals through high surface area, π–π interactions, and defect-induced charge transport, while metal and metal oxide nanomaterials contribute electrocatalytic active sites that lower redox overpotentials and accelerate reaction kinetics [43-45]. In metal–graphene nanohybrids, synergistic coupling between conductive graphene networks and catalytic metal centers enables rapid electron shuttling and reduced charge-transfer resistance, resulting in amplified faradaic currents. Additional amplification is achieved through redox mediator cycling, bimetallic catalysis, heteroatom doping, molecularly imprinted polymers, enzyme inhibition pathways, and advanced voltammetric techniques that suppress background currents. Collectively, these strategies significantly improve sensitivity, selectivity, and signal-to-noise ratios, making electrochemical sensors viable for real-time, on-site monitoring of pesticide residues in complex environmental and food matrices.

3.3 Synergistic Effects in Metal–Graphene Nanohybrids

Combining graphene with metal or metal oxide nanoparticles results in synergistic enhancements that surpass the performance of individual components. Graphene serves as a conductive scaffold that prevents nanoparticle aggregation, while metals provide catalytic active sites for efficient redox reactions.

In metal–graphene nanohybrids, pesticide molecules are first adsorbed onto graphene through non-covalent interactions, followed by catalytic oxidation or reduction at adjacent metal sites [46]. The intimate contact between graphene and metal nanoparticles facilitates rapid electron transfer, lowers charge transfer resistance, and amplifies electrochemical signals. This dual-function mechanism results in improved sensitivity, lower detection limits, and enhanced selectivity.

The formation of metal–graphene interfaces induce electronic coupling and charge redistribution, which modifies the local density of states and enhances catalytic efficiency. In bimetallic or doped graphene systems, additional synergistic effects further optimize electron transfer kinetics and adsorption behaviour, making these hybrids particularly effective for detecting trace-level pesticide residues in complex environmental matrices [47-48].

Table 2: Comparative Performance of Graphene-Based and Metal-Based NM’s

Parameter	Graphene-Based Nanomaterials	Metal-Based Nanomaterials	Metal–Graphene Nanohybrids
Electrical conductivity	Very high	Moderate to high	Very high
Catalytic activity	Limited (enhanced by doping)	High	Synergistically enhanced
Sensitivity	Moderate	High	Very high
Selectivity	Moderate	Moderate	High
Stability	High	Moderate	High
Susceptibility to aggregation	Low	High	Low
Cost	Low to moderate	Moderate to high	Moderate
Suitability for field sensors	Moderate	Moderate	Excellent

3.5 Critical Insights and Challenges

While graphene-based materials excel in electron transport and adsorption capacity, their limited intrinsic catalytic activity necessitates surface modification or hybridization. Metal-based nanomaterials offer superior catalytic performance but suffer from stability and aggregation issues. Metal–graphene nanohybrids effectively address these limitations; however, challenges such as synthesis reproducibility, scalability, and long-term environmental safety remain unresolved.

3.6 Outlook for Electrochemical Pesticide Sensing

Future research should focus on rational design of metal–graphene interfaces, development of green synthesis strategies, and validation of sensor performance under real environmental conditions. Integrating these nanohybrids into flexible, wearable, and wireless sensing platforms will further enhance their applicability for real-time pesticide monitoring and regulatory compliance.

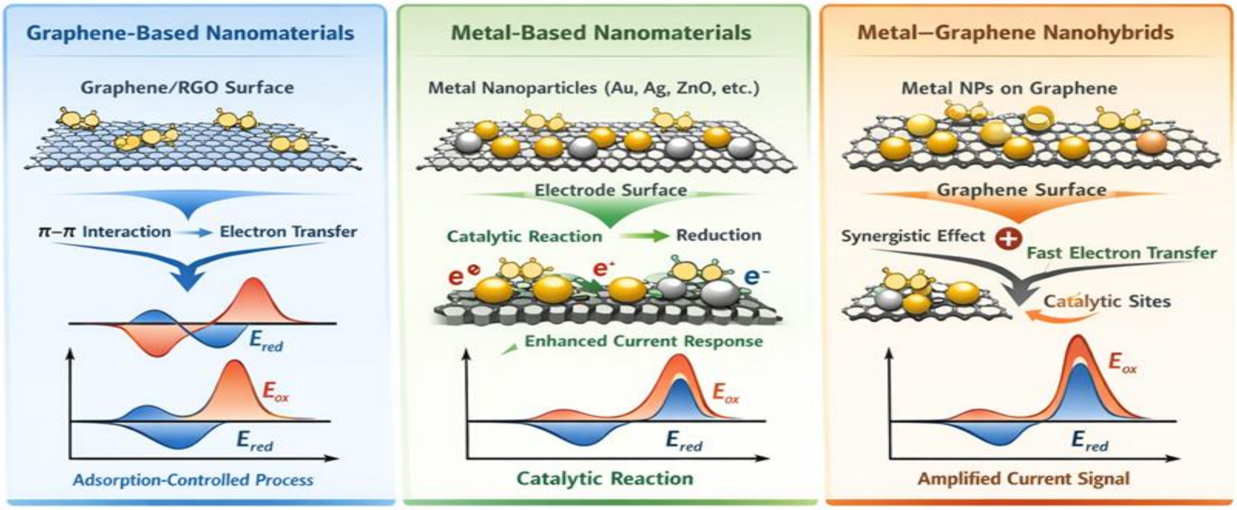

Fig: 2 Schematic representation of mechanism involved in the nano hybrids

IV. REMEDIATION OF PESTICIDES USING METAL AND GRAPHENE-BASED NANO HYBRIDS

The remediation of pesticide-contaminated environments remains a major global challenge due to the persistence, toxicity, and bio accumulative nature of many pesticide classes. Conventional treatment methods, including adsorption using activated carbon, chemical oxidation, and biological degradation, often suffer from limited efficiency, secondary pollution, or poor selectivity. In recent years, metal and graphene-based nanohybrids have emerged as promising multifunctional materials for pesticide remediation, offering synergistic advantages that combine high adsorption capacity, catalytic activity, and efficient electron transfer.

Graphene and its derivatives serve as excellent support materials due to their high specific surface area, chemical stability, and strong affinity toward aromatic and heterocyclic pesticide molecules through π–π interactions, electrostatic attraction, and hydrogen bonding. However, graphene alone primarily acts as a passive adsorbent, with limited capability for complete mineralization of pesticide residues. The integration of metal or metal oxide nanoparticles onto graphene frameworks significantly enhances remediation performance by introducing active catalytic sites capable of driving redox and degradation reactions.

Metal-based components such as Fe_3O_4, CuO, ZnO, TiO_2, and noble metals (Au, Ag, Pt) enable diverse remediation mechanisms, including adsorption-assisted catalysis, advanced oxidation processes, and photocatalytic degradation [49-51]. Transition metal oxides, particularly iron- and copper-based systems, facilitate Fenton-like reactions, generating reactive oxygen species (•OH, $•O_2^-$) that oxidatively decompose persistent pesticides. When coupled with graphene, these systems exhibit improved electron transport, suppressed charge recombination, and enhanced catalytic efficiency. TiO_2–graphene and ZnO–graphene hybrids further exploit photoinduced charge separation under light irradiation, enabling solar-assisted degradation of organophosphate, organochlorine, and neonicotinoid pesticides.

Magnetic metal–graphene nanohybrids, such as Fe_3O_4–graphene composites, offer additional advantages in remediation by enabling rapid magnetic separation and reuse, addressing concerns related to nanoparticle recovery and secondary contamination. These materials demonstrate strong adsorption toward pesticide molecules, followed by catalytic degradation, supporting a combined “capture-and-destroy” remediation strategy. Noble metal–graphene hybrids, while more expensive, exhibit superior catalytic activity and resistance to surface poisoning, making them suitable for treating low-concentration yet highly toxic pesticide residues.

Despite these promising attributes, several critical challenges hinder the large-scale application of metal–graphene nanohybrids in environmental remediation. Issues such as metal ion leaching, nanoparticle aggregation, loss of catalytic activity over repeated cycles, and potential ecotoxicological risks remain insufficiently addressed. Furthermore, most remediation studies are conducted under ideal laboratory conditions, with limited evaluation in complex real-world matrices such as agricultural runoff or wastewater containing competing ions and natural organic matter.

Future research should prioritize the development of sustainable and green synthesis routes, stability-enhanced hybrid architectures, and comprehensive life-cycle and ecotoxicity assessments. Emphasis on scalable fabrication, regeneration efficiency, and field-level validation will be critical for translating metal–graphene nanohybrids from laboratory research to practical environmental remediation technologies. Overall, while metal and graphene-based nanohybrids represent a powerful class of materials for pesticide remediation, their successful deployment will depend on balancing performance, sustainability, and environmental safety.

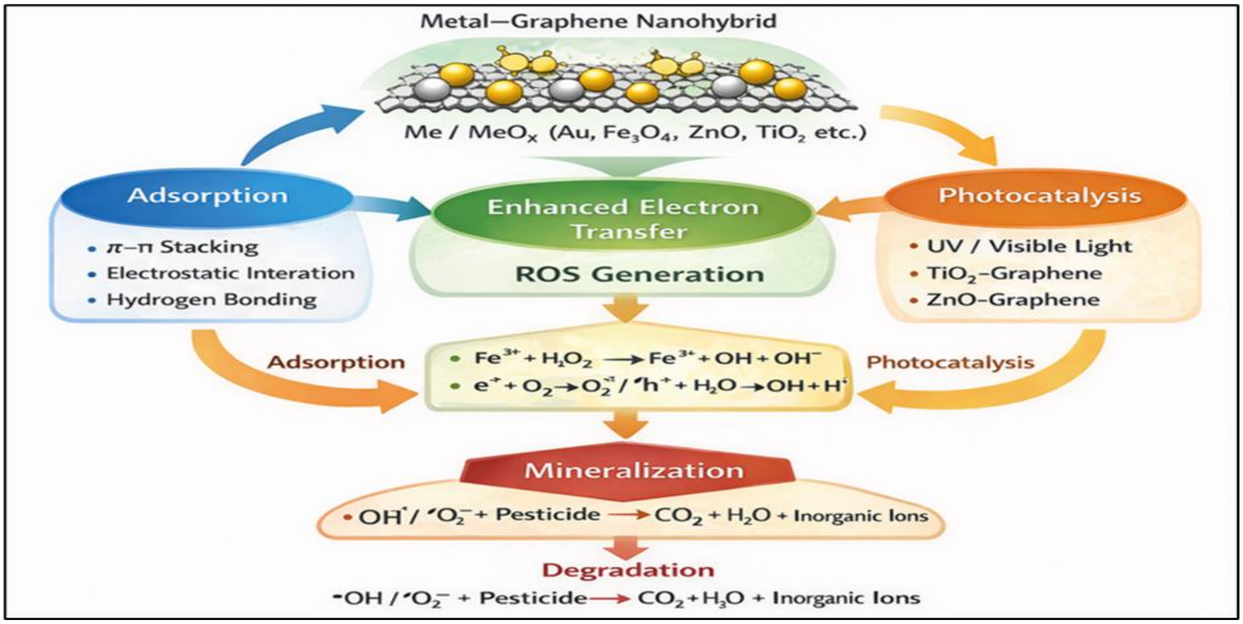

Fig: 3 Synergistic Remediation mechanism of M-Graphene nano hybrids for pesticide degradation

Table 4. Photo catalytic and electro catalytic degradation of pesticides using metal–graphene nanohybrids

Nanohybrid	Target pesticide	Process type	Light/Voltage condition	Degradation efficiency (%)	Time (min)
TiO_2–Graphene	Malathion	Photocatalytic	UV/Vis light	~90 (reported for malathion)	~80
ZnO–rGO	Dimethoate	Photocatalytic	UV/visible light	Noted enhancement relative to ZnO (~>80)	~120
Ag–rGO	Chlorpyrifos	Photocatalytic	Sunlight	high (optimized conditions)	~90
Graphene oxide–TiO_2	Dichlorvos	Photocatalytic	UV lamp	~80	~80
Cu-doped TiO_2/GO	Chlorpyrifos	Photocatalytic	UV/Vi's light	~91	~100
Fe_3O_4–graphene	Not specific pesticide	Photocatalytic (analogue)	Visible light	>90 (for dyes)	~100
NiO-rGO	Model pollutant (MO)	Photocatalytic (analogue)	Visible light	~90	~90
Graphene-metal composite electrode	Paraquat (herbicide)	Electrocatalytic sensor / degradation	Electrochemical (sensor potentials)	sensor response high*	
Nitrogen-doped graphene–Fe based electrode	Pesticide mix	Electrochemical degradation	Electrochemical	high (performance reported)	
Graphene-based E-Fenton catalyst	Organic contaminants including pesticides*	Electro catalytic advanced oxidation	Electro-Fenton (voltage applied)	high removal	

The results in Table 4 clearly show that hybrid catalysts achieve over 85–95% degradation efficiency within a relatively short time. The combination of visible-light absorption and superior electron mobility in graphene enhances catalytic performance, making these materials ideal for real-world environmental cleanup.

V. COMPARATIVE ANALYSIS OF DETECTION AND REMEDIATION EFFICIENCY

Metal–graphene nanohybrids demonstrate superior overall performance in both electrochemical detection and remediation of pesticides compared to standalone graphene or metal-based nanomaterial, owes to their synergistic structural and electronic integration. In electrochemical detection, graphene-based materials primarily enhance sensitivity through high surface area, rapid electron transport, and strong adsorption of pesticide molecules, enabling low detection limits. However, their limited intrinsic catalytic activity often results in slower kinetics and reduced selectivity. Metal nanoparticles or metal oxides, on the other hand, provide strong electro catalytic activity and improved selectivity toward specific pesticide classes but may suffer from aggregation, poor stability, and limited conductivity. Metal–graphene nanohybrids overcome these limitations by combining graphene's conductive network with metal-induced catalytic sites, leading to faster electron transfer, lower over potentials, higher signal amplification, and detection limits frequently reaching the nano- to Pico molar range.

In remediation applications, graphene-based materials excel in rapid adsorption of pesticides but largely function as passive sorbents, necessitating additional treatment steps for complete detoxification. Metal and metal oxide nano materials enable catalytic and photo catalytic degradation through reactive oxygen species generation but often experience high charge recombination rates and poor reusability. Metal–graphene nanohybrids exhibit markedly enhanced remediation efficiency by facilitating adsorption-assisted catalysis, efficient charge separation, and sustained ROS production. Systems such as Fe_3O_4–graphene, TiO_2–graphene, and ZnO–graphene achieve higher degradation rates, improved mineralization efficiency, and better recyclability than their individual counterparts. Nonetheless, while hybrid materials consistently outperform single-component systems, challenges related to long-term stability, metal leaching, and real-matrix performance still limit their large-scale deployment. Overall, metal–graphene nanohybrids represent the most balanced and effective platform for integrated pesticide detection and remediation, provided sustainability and environmental safety concerns are adequately addressed.

Detection favours conductivity and surface chemistry, remediation favours catalytic activity and metal graphene nanohybrids uniquely bridge both requirements.

5.1 Critical Analysis and Gaps Identification

Metal–graphene nanohybrids demonstrate significantly enhanced performance compared to pristine materials, achieving 10–100-fold improvements in sensitivity and remediation efficiency due to synergistic effects between graphene and metal or metal oxide components [52]. Despite these advantages, several critical gaps limit their translational potential. Scalability remains a major challenge, as most laboratory syntheses are costly, time-intensive, and prone to nanoparticle aggregation [53]. Comprehensive toxicity assessments are lacking; potential bioaccumulation and eco toxicological impacts of these nanohybrids remain largely unexplored [54]. Performance validation in real environmental matrices is insufficient, with many studies relying on spiked samples that overlook complex interferents, potentially overestimating efficacy [55-56]. In remediation applications, concerns over toxic by-products, energy inefficiency, and limited applicability to emerging pesticides, such as neonicotinoids in organic-rich environments persist [57-58]. Furthermore, regulatory frameworks for nanomaterial deployment in environmental applications are underdeveloped, delaying commercialization. Addressing these challenges requires standardized synthesis and testing protocols, comprehensive environmental risk assessments, and interdisciplinary collaboration to bridge laboratory innovation with practical, field-ready solutions.

VI. CONCLUSIONS

Metal–graphene nanohybrids represent a transformative approach for integrated management of environmental pesticides, combining sensitive electrochemical detection with efficient remediation. Graphene's high conductivity, large surface area, and adsorption capability synergize with the catalytic activity of metals and metal oxides to deliver rapid, selective detection of organophosphates, carbamates, and triazines. Simultaneously, these hybrids enable photo catalytic and electro catalytic degradation, often achieving over 90% removal efficiency while maintaining stability and reusability. Despite their promise, challenges such as scalable synthesis, metal leaching, long-term stability, and performance in complex real-world matrices remain. Future research should focus on green, plant-assisted synthesis, multifunctional hybrid designs for simultaneous detection and detoxification, three-dimensional or hierarchical architectures for enhanced electron transport and catalytic efficiency, and integration with AI-driven optimization and IoT-enabled portable devices. By addressing these gaps, metal–graphene nanohybrids can transition from laboratory demonstrations to field-deployable solutions, offering a sustainable, high-performance platform for real-time pesticide monitoring and remediation, and paving the way toward global environmental safety and agricultural sustainability.

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