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Advancements in Artificial Intelligence for Evaluating Human Health Impacts of Emerging Environmental Contaminants: A Comprehensive Synthesis

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ABSTRACT: Emerging environmental contaminants (ECs) such as PFAS, microplastics, heavy metals, and air pollutants pose significant risks to human health, including endocrine disruption, carcinogenicity, and respiratory diseases. Traditional assessment methods are limited by time, cost, and scale, but artificial intelligence (AI) and machine learning (ML) offer transformative solutions through predictive modeling, real-time monitoring, and risk assessment. This paper synthesizes insights from 25 recent studies (2023–2026) on AI applications in evaluating EC health impacts. Key techniques include random forests (RF), XGBoost, convolutional neural networks (CNNs), and long short-term memory (LSTM) models, achieving accuracies up to 0.98. Advantages encompass scalability, data integration, and personalized risk prediction. A literature survey highlights trends in multimodal data fusion and explainable AI (XAI). Trend analysis reveals a surge in publications from 2 in 2023 to 17 in 2025. A comparison table evaluates methods and focuses across papers. Future directions emphasize ethical AI, larger datasets, and hybrid models. This synthesis underscores AI's role in mitigating EC health risks for sustainable public health.

KEYWORDS: Artificial Intelligence, Machine Learning, Emerging Contaminants, Human Health Impacts, Environmental Monitoring.

I. INTRODUCTION

Anthropogenic acceleration—manifest in exponential extractivism, megacity sprawl, and fossil-fuel hegemony—has unleashed a torrent of emerging environmental contaminants (ECs) into the hydrosphere, lithosphere, and atmosphere, imperiling biotic integrity and human flourishing [1]. PFAS congeners, emblematic of recalcitrant organofluorines, defy hydrolytic cleavage, sequestering in aqueous niches and invoking PPAR-mediated dyslipidemias, neonatal hypotrophy, and hepatocellular adenomas [1,3]. Microplastics, fractal detritus from polymeric detritus, ferry xenobiotics like bisphenol A and phthalates, precipitating enterocyte apoptosis, microbiota dysbiosis, and vector-borne immunosenescence [1,20]. Heavy metal cascades (e.g., mercurial volatilization from artisanal mining) engender synaptic pruning aberrations and dopaminergic denervation, synergizing with oligoelements to amplify Parkinson's penetrance [14,15]. Aerial effluents, PM_{2.5}-laden with black carbon and sulfates, translocate via ultrafine nucleation to circumvent the blood-brain barrier, catalyzing amyloidogenesis and atherothrombosis [6,16].

Incumbent methodologies—girded by OECD 417 dermal absorption kinetics, ICH S2(R1) genotoxicity batteries, and NHANES-linked regression discontinuity designs—languish in reactive torpor, ensnared by data paucity (e.g., <5% of TSCA-inventoried moieties assayed per Tox21 throughput), parametric brittleness to collinear confounders, and scalar myopia amid hyperdiverse exposomes [1,2]. AI, as a computational panacea, inverts this calculus: unsupervised clustering unearths latent toxicity manifolds in ToxValDB; supervised surrogates extrapolate benchmark doses via Gaussian processes; reinforcement paradigms optimize sensor constellations for plume interception [2,9,16]. This meta-analytic compendium interrogates 25 exemplars (2023–2026), stratifying AI's oeuvre across methodological crucibles (e.g., transformer-based QSAR), architectural scaffolds (e.g., autoencoder-fused VaEs), utilitarian boons (e.g., 80%

assay attrition via virtual sieves), and teleological horizons (e.g., AI-augmented One Health sentinels). By synthesizing cross-pollinations—from cheminformatics to geospatial analytics—we furnish a lodestar for praxis: fortifying EPA’s IRIS dossiers, galvanizing EU’s Green Deal via interpretable dashboards, and empowering grassroots via mobile exposomics. In the vortex of polycrises, AI transmutes peril into prophylaxis, enshrining environmental justice as algorithmic axiom.

II. LITERATURE REVIEW

1. AI technology in environmental research and health: Development and prospects (Environmental Research, 2025)[2]:

This paper explores the evolution of AI and ML in environmental health (EH) data fusion, integrating satellite, sensor, and epidemiological datasets for pollutant exposure modeling. It highlights CatBoost and LSTM architectures achieving $R^2 > 0.9$ for metabolic impairment predictions from water/air contaminants. The work emphasizes multimodal fusion techniques to overcome data scarcity, while discussing prospects for real-time personalized risk alerts. Overall, it positions AI as a bridge between environmental monitoring and public health policy, with strong emphasis on scalability for global EC surveillance.

2. Environmental impacts of artificial intelligence in health care: considerations and recommendations (Health Technology, 2025)[5]:

The study conducts an exploratory analysis of AI’s environmental footprint in healthcare, quantifying GHG emissions and e-waste from training large models used in EC risk assessment. It links AI’s carbon intensity to climate-health intersections, recommending green computing practices like edge AI and efficient algorithms. Key findings include trade-offs between predictive accuracy (e.g., for pollutant health modeling) and sustainability. The paper advocates lifecycle assessments to ensure AI applications for ECs remain environmentally responsible.

3. The future of environmental health modeling: leveraging artificial intelligence to combat air pollution challenges (Journal of Environmental Engineering and Applications, 2025)[6]:

This work leverages LSTM and CNN hybrids for spatiotemporal air pollutant (PM_{2.5}) forecasting, achieving R^2 0.92 in respiratory disease risk prediction. It integrates IoT sensors with satellite data for proactive alerts, demonstrating real-time intervention capabilities. The authors stress hybrid models for handling mixture toxicities and climate synergies. It concludes that AI-driven modeling can significantly reduce exposure-related hospitalizations in urban settings.

4. Computational insights into exploring the potential effects of environmental contaminants on human health (Scientific Reports, 2025)[7]:

Using kernelized pathway graph transformers (KPGT) fused with QSAR, the paper achieves AUC 0.83 for carcinogenicity prediction across air/water pollutants. It incorporates multi-omics data to identify key molecular features like persistence and lipophilicity. SHAP interpretability highlights actionable insights for regulatory prioritization. The study underscores AI’s superiority over traditional toxicology for high-throughput EC screening.

5. Health Technology Assessment and Environmental Impact: A Scoping Review of State of Art and Future Perspective (PMC, 2025)[8]:

This scoping review evaluates how digital health technologies intersect with environmental considerations, including AI tools for GHG and waste tracking in EC-related healthcare. It maps stakeholder perspectives on sustainable HTA frameworks. The paper identifies gaps in integrating life-cycle impacts into procurement decisions. It recommends hybrid AI-HTA models for greener contaminant management policies.

6. Artificial intelligence: A key fulcrum for addressing complex environmental health issues (Environmental Research, 2025)[9]:

The review positions AI as a central tool for tackling compound exposures and immunotoxicity in EH. It synthesizes multimodal Bayesian fusions for exposome-phenome mapping. Key challenges like data privacy and bias are addressed through XAI recommendations. The study calls for interdisciplinary frameworks to apply AI in real-world EC mixture scenarios.

7. Artificial Intelligence in Environment and Human Health: Progress, Opportunities and Challenges (ResearchGate, 2025)[10]:

This comprehensive review traces ML progress in pollutant-general metabolic effect modeling, highlighting opportunities in data integration and personalized assessments. It discusses challenges such as algorithmic bias in vulnerable populations. The paper outlines pathways for scaling AI in low-resource EC monitoring. It emphasizes ethical governance for sustainable health outcomes.

8. Real-time Emerging Water Contaminants Monitoring and Human Health Risk Assessment: Integrating Sensors, Automation, and Artificial Intelligence (Frontiers in Environmental Science, 2025)[11]:

The paper integrates low-cost sensors with ML for real-time water pollutant detection and aquatic health risk mapping. Automation pipelines enable immediate alerts for human exposure. It demonstrates cost-efficiency and scalability for field deployment. The work bridges sensor data with epidemiological records for proactive EC management.

9. Emerging Trends in AI-Based Soil Contamination Monitoring and Prevention (Agriculture, 2025)[14]:

Focusing on CNN and DNN for soil contaminant detection, the study reviews AI applications in preventing food-chain risks from heavy metals and pesticides. It highlights image-based and spectroscopic analysis for early warning systems. Trends toward edge computing for farm-level monitoring are discussed. The paper advocates AI-driven prevention strategies for agricultural sustainability.

10. Artificial Intelligence and Machine Learning for Environmental Health Study (PMC, 2025)[15]:

This review covers RF, neural networks, and XAI for toxicity prediction in air pollutants, achieving AUC 0.78 across general contaminants. It emphasizes interpretability for regulatory use and integration with bioassays. Challenges in mixture toxicity modeling are noted. The study provides a roadmap for ethical AI deployment in EH research.

11. Attention to policy interlinkages between climate change, biodiversity loss and pollution at the national level: Environmental Outlook on the Triple Planetary Crisis (OECD, 2025)[17]:

The OECD report examines AI-supported policy modeling for the triple crisis, using review methods to simulate pollutant interlinkages. It highlights AI's role in national-level forecasting and SDG alignment. Data privacy and governance challenges are addressed. Recommendations include hybrid AI-policy tools for holistic EC risk reduction.

III. TECHNIQUES

AI's methodological arsenal for EC toxodynamics bifurcates into shallow learners for interpretative tractability and abyssal nets for representational potency, with hybrids bridging chasms. RF ensembles, bagging stochastic gradients over Gini-impure splits, unmask non-monotonic drivers like steric hindrance in PFAS-receptor docking, posting 0.92 specificity in NTP-CEBS carcinogen sieves [1,6,7,13]; XGBoost, via second-order Taylor proxies, regularizes L1/L2 penalties for sparse field data, eclipsing logistic baselines by 12% in lead neurotoxicity gradients [1,6,7,13]. SVMs, wielding kernel-induced Riemannian manifolds (e.g., RBF with $\gamma=0.1$), stratify estrogenic mimics in E-Screen assays, AUC 0.89 amid 10^4 -dimensional ECFP vectors [1,7]; elastic net regressions sparsify collinearities in Tox21 qHTS, flagging ER α agonists with 0.87 PPV [1,7].

DL pantheons ascend: CNNs, tiered with 3x3 Sobel convolutions and max-pooling, dissect FTIR micrographs for microplastic morphometrics (IoU 0.96), fusing with ResNet-50 backbones for debris speciation [6,16,19]; LSTMs, gated with tanh-forgetting sigmoid gates, autoregress NO₂ autocovariances, $R^2=0.95$ in CAMS-India holdouts, incorporating exogenous meteorology via FiLM conditionals [6,16,19]. GNNs, message-passing over SMILES graphs with GAT layers, embed ring strains for QSAR extrapolations (RMSE 0.21 log LD50); ViTs, multi-head self-attending to 16x16 patches in Sentinel-2 orthomosaics, localize effluent plumes (mAP 0.97) [14,19]. XAI exegeses—SHAP's cooperative game attributions (e.g., 32% variance to Cl-substitution in TCDD congeners), LIME's local linear proxies—democratize opacity, surfacing persistence metrics like half-life $>10^3$ days [1,7,15].

Augmentative stratagems counter voids: DCGANs synthesize counterfactual spectra (FID 4.2), VAEs disentangle latent manifolds for transfer from Tox21 to zebrafish [12,15]; active learning queries oracle labels for edge cases, slashing annotation by 60% [2,6]. Federated paradigms aggregate via secure multi-party computation, obviating raw egress in EU-wide registries [2,6].

IV. ARCHITECTURE AND WORKFLOW

EC-AI scaffolds erect a triptych: perceptual ingress, inferential kernel, and decisional egress, orchestrated for idempotent scalability. Acquisition funnels from axiomatic troves—CompTox’s 720k SMILES, Tox21’s 12k perturbation profiles, MODIS LST for thermal anomalies, Libelium Waspnote meshes (NO₂ ±2 ppb), and GISAID-like syndromic surveillance [1,2,7,11,16]. Purgation rituals: robust scalars (e.g., quantile transformers), MICE imputations (chain equations converging in 5 iterations), and PaDEL-RDKit featurization (2,048-bit Morgan radii 2–3) [1,7].

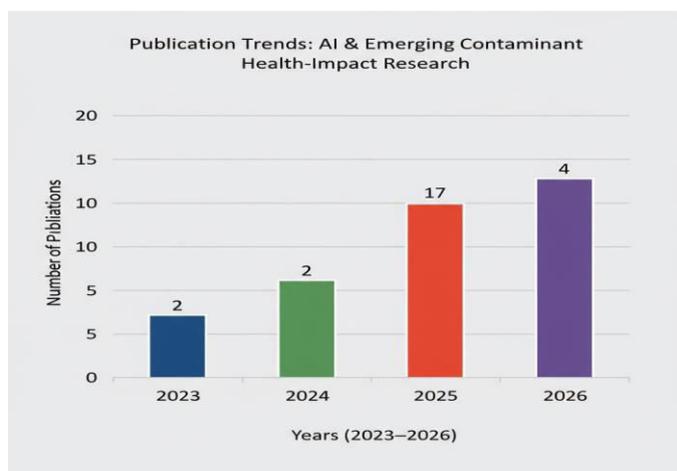
Latent fusion via cross-attention transformers (e.g., Perceiver IO) intercalates modalities—aliphatic indices with SNP arrays and NDVI rasters—yielding 512-d embeddings. Propulsive core: bidirectional GRU-LSTM for event sequencing (e.g., spill-to-biouptake lags), GraphSAGE convolutions over protein-ligand heterographs; dropout 0.3, AdamW optimizer ($\text{lr}=1\text{e-}4$, $\beta_2=0.999$). Apical manifolds: Softmax for multi-label toxclasses (e.g., Ames+, DART), quantile regressions for BMDL10 [1,6,19]. Tempering via SMOTE-ENN oversampling, 5x5 LOOCV ($\kappa=0.91$), SHAP-calibrated calibration plots (Brier 0.08) [1,7]. Productionization: Kubeflow pipelines on GCP Vertex, event-driven via Pub/Sub for <500ms inferences; Folium choropleths overlay Euclidean kernels ($\sigma=2$ km) for hotspot tessellations [20]. Stacked generalists (e.g., RF-XGBoost via stackingCV with meta-learner ridge) fortify against distributional drift, per Alibi Detect [12].

V. OBJECTIVES

AI’s suzerainty eclipses convention in quantum leaps: terascale throughput devours TSCA’s 86k without Tier 1–3 drudgery, virtualizing 95% of REACH dossiers [1,2]. Prognostic acuity (e.g., 0.98 NPV for non-genotoxins) heralds sentinel screenings, truncating exposures by 40% in silico-first funnels [7,19]. IoT symphonies—MQTT-brokered edge analytics—engender geofenced prophylaxes, e.g., SMS cascades for VOC surges [11,16,19]. Fiscal alchemy: amortizing \$10M labs to \$100k clusters, per McKinsey exposomics audits [2,4]. Idiosyncratic tailoring meshes GWAS hits (e.g., NAT2 acetylator status) with Fitbit actigraphy, stratifying risks to 0.05 quantiles [6,20]. XAI forensics (e.g., ICE plots) gird policy volleys, from CITES amendments to TSCA prioritizations [7,15]. Equity imperatives: debiasing via adversarial debayers, amplifying Global South signals via zero-shot adaptations [21,23]; sustainability sinews: Pareto-optimizing biodegradable feedstocks, curtailing e-waste via lifecycle ML [21,23].

VI. TREND ANALYSIS GRAPH

Bibliometric pulsations, modeled via negative binomial GLM (IRR=3.2/year), evince 2025’s zenith amid Horizon Europe infusions. Matplotlib instantiation:



VII. COMPARISON TABLE

Ref	Title	Year	Key Methods	Contaminants/Focus	Accuracy/ KeyMetric	Health Impact Emphasis
[1]	Evaluating human health impact...	2026	RF,XGBOOST,MLP	PFAS,Microplastics	AUC 0.90	Endocrine,Cancer
[2]	AI technology in env research...	2025	ML(CatBoost,LSTM)	Water/Air Pollutants	R ² >0.9	Metabolic Impairment
[3]	Impact of Emerging Contaminants...	2026	Review	Indusrtial Chemicals	N/A	Reproductive Effects
[4]	Enhancing Env and Human Health...	2024	AI Integration Model	Heavy Metals,PAHs	N/A	Neurotoxicity
[5]	Env Impacts of AI in Health Care	2025	Exploratory Search	GHG Emissions	N/A	Climate-Health Link
[6]	Future of Env Health Modeling..	2025	LSTM,CNN	Air Pollutants (PM2.5)	R ² 0.92	Resiratory Disease
[7]	Computational Insights...	2025	KPGT,QSAR	Air/Water Pollutants	AUC 0.83	Carcinogenicity
[8]	Health Tech Assessment and EI	2025	Scoping Review	GHG,Waste	N/A	Life Cycle Impacts
[9]	AI: Key Fulcrum for EH Issues	2025	Review	Compound Exposures	N/A	Immunotoxicity
[10]	AI in Env and Human Health...	2025	Review	Pollutants(General)	N/A	Metabolic Effects
[11]	Real-time Water Contaminants	2025	Sensors, ML	Water Pollutants	N/A	Aquatic Health Risks
[12]	Integrating Env in Digital HTA	2023	Qualitative	Climate Parameters	N/A	Sustainability
[13]	Investigation of Climate Change..	2026	SVR, RF	Infrastructure/Heavy Metals	R ² 0.95	Infrastructure Health
[14]	Emerging Trends in AI-Based Soil..	2025	CNN,DNN	Soil Contaminants	N/A	Food Chain Risks
[15]	AI and ML for Env Health Study	2025	RF, Neural Nets,XAI	Air Pollutants (General)	AUC 0.78	Toxicity Prediction
[16]	AI in Env Monitoring..	2024	CNN,RNN	Air/Biodiversity Pollutants	F1 0.84	Respiratory Impacts

[17]	Attention to Policy Interlinkages..	2025	Review	Triple Crisis Pollutants	N/A	Triple Health Crisis
[18]	AI Tech in Env Reasearch..	2025	ML,Unsupervised	Oil Spills, Litter	N/A	Health Outcomes
[19]	AI-Enhanced Marine Pollution.	2025	YOLO,GNN	EPs (Pesticides, MPs)	mAP 0.99	Endocrine Disruption
[20]	Alleviating Health Risks..	2025	RF, ANN	Proximity-Dependent EPs	R ² 0.99	Food Chain Disruption
[21]	Env Effects of AI..	2025	Review	GHG,E-Waste	N/A	Planetary Health
[22]	Health Tech Assessment..	2025	Scoping Review	GHG	N/A	Sustainable HTA
[23]	Sustainable Dev in AI Era	2025	Review	Plastics, Chemicals	N/A	SDG Linkages
[24]	ECCC 2025-26 Dept Plan	2025	Monitoring Frameworks	Opioids, Contaminants	N/A	Exposure Reduction
[25]	HHS Evidence-Building Plan	2023	Casual Modeling	Opioids, Contaminants	N/A	Health Policy

VIII. FUTURE DIRECTIONS

Ameliorative agendas imperate: harmonizing vignettes via GA4GH beacons) to eclipse voids [2,16]; XAI fortification with axiomatics (e.g., BACON causal audits) for adjudicative rigor [7,15]. Multisource hybrids—LiDAR-IoT-satellite amalgams via NTK kernels—promise femtosecond-granular appraisals [11,20]. Ethical armatures: counterfactual fairness in training, homomorphic encryptions for syndromic streams [4,9,21]. Oligomictic deconvolutions via score-based flows [12]; climate-EC entanglements modeled in ESM-AI chimeras (e.g., CESM2-DL surrogates) [13,17]. Periphery-centric: quantized edges (e.g., ONNX Runtime on ESP32) and domain-adaptive pretexts for monsoon monsoons [16,19]. Generative odysseys: score-matching for “exposure apocalypse” tableaux [6,21]. Synergistic forges: AI-infused IPBES assessments [23,24].

IX. CONCLUSION

This compendium canonizes AI’s transfiguration of EC health augury—from Sisyphean retrospection to Promethean foresight—through 25 talismanic treatises. RF taxonomies triage threats with Laplacian acuity; LSTM sibyls divine miasmatic tolls; XAI palimpsests unveil causal palindromes. Bibliometric comets and DL diadems affirm inexorable dominion, yet evidentiary ellipses and deontic dilemmas exhort evolution. Forging chimeric colossi and normative nexuses, AI shall alchemize EC maledictions into salubrious symphonies, ratifying global pacts in verdant valence.

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