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REVIEW

From Reactor to Receptor: Coupled Chemical Cycles of Industrial Pollutants across Atmospheric, Pedologic, and Groundwater Systems

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ABSTRACT

This review is based on the synthesis of the movement and transformation of industrial pollutants between the sources of emissions and the human and ecological receptors based on the tight-knit chemical processes involving the atmosphere, soil, and groundwater. Instead of taking linear source-pathway-receptor routes, several contaminants are subjected to repetitive partitioning, reaction, retention, and remobilization among environmental compartments. We define the reactor-to-receptor continuum based on the idea of connecting attributes of sources (speciation, phase state, volatility, and reactivity) to atmospheric effects (processing, deposition, and exchange). There is atmospheric oxidation, photochemistry, and gas-particle partitioning, which change the composition of the pollutants and dictate the chemical form that is deposited on the land surfaces. Soil sorption to organic matter and minerals, pH, and redox-specified reactions, and reactions facilitated by microorganisms control mobility, persistence, and bioavailability, and provide environments of secondary emissions and retarded leaching. Through vadose zone transport and aquifer transport, underground transport provides long-term retention and selective redox conditions capable of neutralizing the contaminants by precipitation and biodegradation, or producing mobile and toxic daughter products. We focus on feedback from the emphasized system, the nonexposure to the underlying induction of the disturbance, and, for the example of legacy contamination, we refer to the predominance of long-term risk as the dominant driver. Lastly, we assess combined modeling and monitoring solutions that can solve cross-media fluxes and transformations, and also, we talk about their implications for exposure assessment, regulation, and sustainable industrial design.

Keywords: Coupled Chemical Cycling; Atmospheric Deposition; Soil-Groundwater Interactions; Legacy Contamination; Multimedia Fate Modeling

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1. Introduction

The industrial activity has transformed biogeochemical cycles of the world, as massive amounts of artificial and mobilized natural chemicals have been introduced into the environment [1,2]. Since the high-temperature reactors, manufacturing plants, and regions of waste treatment are all sources of pollution, the released or emitted contaminants move through complex and frequently poorly than well-defined routes in air, soil, and water. Conventional measurements of industrial pollution have generally been linear, that is, emissions, transport, exposure, and effects, and the atmosphere, soils, and groundwater have been treated as very distinct compartments [3,4]. Although this method produced significant regulatory and technological gains, it has become less and less successful in describing the dynamic and coupled behavior of pollutants in terms of various environmental systems. Most industrial contaminants are not transported directly between a source and a receptor, but rather they are involved in interacting chemical cycles that connect the realms of the atmosphere, pedology, and groundwater across spatial scales of meters to continents and temporal scales of hours to decades [5,6]. A conceptual overview of the coupled chemical cycles linking industrial reactors to environmental and biological receptors is shown in **Figure 1**.

The reactor-to-receptor concept is concerned with the continuation between the processes of pollutant production, environmental change, and the final human and ecological exposure. The initiation of the physicochemical state of pollutants indicated by industrial reactors, such as speciation, oxidation state, molecular structure, and phase distribution, is very strong in determining the subsequent fate of the pollutants. These properties, however, develop when released into the environment through interactions with environmental matrices, energy gradients, and biological activity. Rapid changes in the pollutant composition can be caused by atmospheric oxidation, photolysis, and gas-particle partitioning, whereas the deposition processes link the atmosphere with terrestrial and water surfaces. The contaminants can be sorbed and mineral-associated in soils, and redox and microbial transformation can be carried out, or remobilization of the contaminants in the soils towards porewaters feeding groundwater (GW) systems. The groundwater, in turn, is not only a long-term storage but also a time delay to the surface water, ecosystems, and drinking water sources. These connected processes create coupled chemical cycles where contaminants can recycle between stages and compartments and deconstruct simple source-pathway receiver paradigms [7,8].

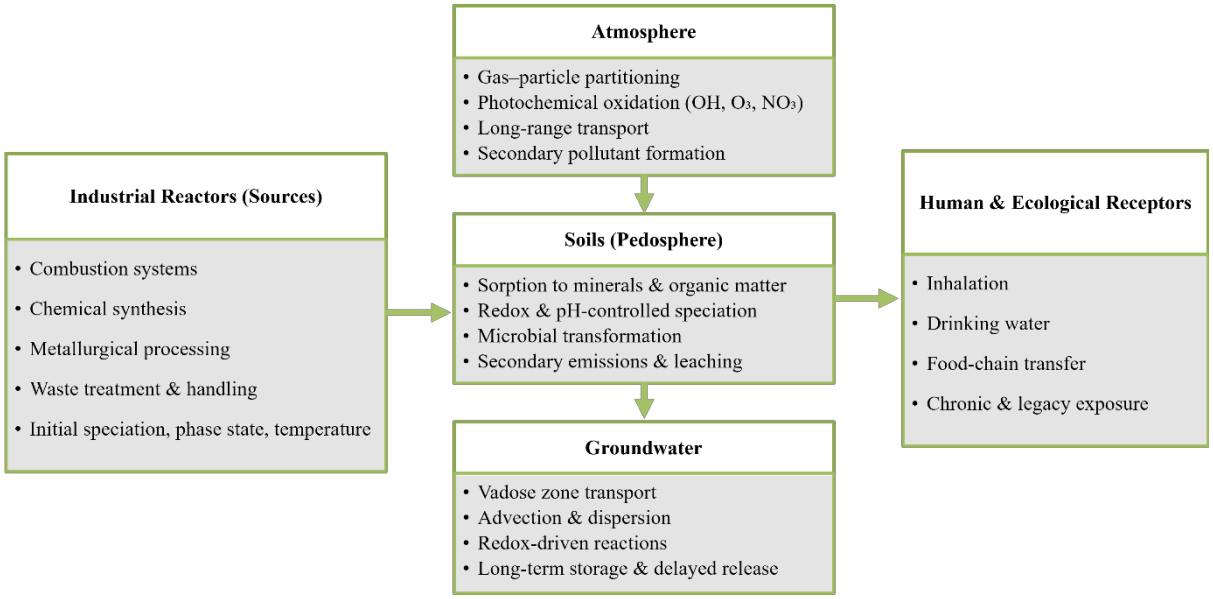

Figure 1. Conceptual framework illustrating coupled chemical cycling of industrial pollutants from reactors to human and ecological receptors across atmospheric, pedologic, and groundwater systems.

Awareness of this kind of coupling has increased with the presence of legacy and long-term contamination. Examples of industrial chemicals moving between reservoirs in the environment include heavy metals, chlorinated solvents, persistent organic pollutants, and, more recently, per- and polyfluoroalkyls. Metal-containing particulates can be deposited in the atmosphere and therefore contaminate the soil, which subsequently becomes a secondary source of emission by resuspension or leaching. Volatile organic compounds and semi-volatiles can be subjected to deposition and re-volatilization cycles due to temperature, land use change, or disturbance. In groundwater systems, exposure pathways may be created by slow advective transport and geochemical transformations that are created decades after first release. The above examples highlight the necessity of integrative frameworks, specifically including cross-media coupling and longer-term system behavior [9,10].

The atmosphere is central in initiating and redistributing industrial pollutants at regional and global levels aerosols [11], of the contaminants are released as gases or aerosol whereas others are released through atmospheric reactions in a secondarily manner. Toxicity, solubility and environmental persistence can also be altered significantly through oxidation, nitration, halogenation and photochemical aging. Notably, the nature of the delivery of pollutants to the earth surfaces usually depends on atmospheric processing in wet and dry deposition forms. Subsequent contributions to soils are not thus but rather simply diluted forms of emissions but chemically altered products whose action in the pedologic environment can differ significantly with their antecedents. On the other hand, soils may serve as a source of contaminants in the atmosphere either through dust entrainment or volatilization, strengthening the concept of both way coupling between the systems [12].

The soils are an important nexus of coupled pollutant cycles that combine the input of the atmosphere, surface water, and the anthropogenic activity of farming and land contamination with industrial by-products [13]. The working of soils as sinks, buffers, or secondary sources of contamination depends on pedologic processes. When pollution moves to the organic and mineral surface by sorption, migration may be slowed down, and under redox gradient, varying pH, and microbial metabolic activity induce transformation pathways between mobility and bioavailability. The distribution of contaminants between the solid phases and porewater is also determined by soil structure and hydrology, and affects how contaminants move downwards into the vadose zone into aquifers. The processes are very heterogeneous spatially and through time, making it difficult to extrapolate site-specific studies to broader environmental contexts.

Another complication to industrial pollutant cycling is the existence of groundwater systems. As soon as contaminants have found their way to the subsurface, they can last a long time under conditions that encourage minimal dispersion but active chemical and biological modification. Altering environments prevalent in aquifers may enhance processes like metal reduction, dechlorination, or conversion of secondary stages in minerals, and this essentially transforms the behaviors of these contaminants. Groundwater circulation links polluted areas to surface water, wetlands, and the drinking water supply with significant time delays. This makes ways of exposure via groundwater central to the context of chronic exposure and historical effects of past industrial activity. However, groundwater is often viewed as a termination instead of an active constituent of the coupled environmental processes [14,15].

Traditional linear source-pathway-receptor models treat the atmosphere, soil, and groundwater as sequential, independent compartments through which pollutants pass en route to receptors. In contrast, we define the reactor-to-receptor continuum as an integrated framework wherein industrial pollutants undergo repetitive partitioning, reaction, retention, and remobilization across interconnected environmental media. This continuum distinguishes itself from linear models through three key features. First, bidirectional coupling means that soils not only receive atmospheric deposition but also re-emit contaminants to the air, while groundwater not only stores pollutants but discharges to surface waters that subsequently volatilize. Second, temporal decoupling refers to the fact that emissions and exposures may be separated by decades due to storage in soil and groundwater reservoirs, thereby creating legacy contamination that linear models cannot capture. Third, transformative cycling recognizes that chemical speciation changes repeatedly across compartments—for example, through atmospheric oxidation, followed by soil

sorption, followed by aquifer reduction—such that receptor exposure is often to transformation products rather than to source-emitted forms. Thus, the continuum emphasizes that industrial reactors imprint initial physicochemical properties, but these properties evolve continuously through coupled atmospheric, pedologic, and groundwater processes until receptors are reached, and sometimes beyond, as receptors themselves may become secondary sources [16–20].

This review seeks to fill these gaps by considering industrial pollutants as actors in coupled chemical cycles that run between the reactors and the receptors. We compile existing information on the source-term properties, atmospheric change and transport, soil-pollutant relationship, and groundwater processes with a special focus on the interconnection of these areas. This article attempts to elucidate the prevailing behavioral patterns of pollutants by establishing a cross-media context in which the prime controls on the interacting couplet may be found, and the direction of future research and policy formulation in industrial environmental management can be identified.

2. Industrial Pollutants and Source-Term Characteristics

The source of industrial pollutants is extremely diverse, covering chemical reactors, metallurgical furnaces, energy conversion, and waste management facilities [21]. The physical situation in which these pollutants are produced, i.e., temperature, pressure, redox, residence time, and feedstock structure, has a strong effect on their original physicochemical properties and, as such, their fate in the environment. The source term in the context of coupled chemical cycles is not simply a quantitative emission term but a qualitative determinant of the way in which the pollutants are going to interact with the atmospheric, pedologic, and groundwater systems. The knowledge of source-term properties is thus important in associating the industrial processes with downstream environment changes and exposure to receptors.

2.1. Classification of Industrial Pollutants

The industrial pollutants constitute a wide range of inorganic and organic compounds that vary significantly in chemical stability, reactivity, and permanence in the environment. Some of the inorganic pollutants are trace and heavy metals that might be emitted in the elemental form, ionic, or particulate-bound form, such as mercury, lead, cadmium, and chromium. It is their solubility, toxicity, and vulnerability to redox-mediated transitions that are dictated by the point at which they are released. Organic pollutants include volatile organic compounds and polycyclic aromatic hydrocarbons, as well as persistent organic pollutants and newer categories of pollutants, including per- and polyfluoroalkyl substances. The compounds differ in terms of molecular weight, functionalization, and volatility, which directly influence phase partitioning and transport. Also, reactive gaseous pollutants such as sulfur and nitrogen-containing species contribute to the formation of both primary and secondary pollutants, since they are the precursors of secondary pollutants produced in the atmosphere by atmospheric chemistry. These classes of pollution are often distinguished as distinct entities, but multiple classes of pollutants regularly act in collocated ways and often create complicated blends that might not be explained by the classic classification systems [22,23].

2.2. Physicochemical Properties Governing Environmental Behavior

Intrinsic physicochemical properties that are set at the source determine the environmental behavior of industrial pollutants to a large degree. Atmospheric oxidants, mineral surfaces, and microbial enzymes reactivity are determined by molecular structure, oxidation state, and functional groups. Volatility and vapor pressure regulate the partitioning of gases and particles between the gases and the solids, and the tendency to be transported in the airways in the atmosphere, whereas solubility and hydrophobicity affect the distribution between the aqueous and the solid phases of soils and aquifers. In the case of metals, speciation regulates both affinity to organic matter and mineral phases and bioavailability and toxicity. These properties are not absolute; they may change when the pollutants undergo some chemical and physical change once released. However, the source-term attributes confine the scope of the potential environmental pathways and precondition the further interconnection

between environmental compartments [7,24]. **Table 1** summarizes the diversity of classes of industrial pollutants and their source-term properties, which dictate future cross-media behavior.

Table 1. Representative industrial pollutant classes, source-term characteristics, and relevance to coupled atmospheric-soil-groundwater cycling.

Pollutant Class	Typical Industrial Origins	Predominant Emission Form(s)	Source-Term Determinants	Cross-Media Relevance (Air–Soil–GW)
Trace/heavy metals (Hg, Pb, Cd, Cr, As)	Smelting, coal combustion, cement, metal finishing	Particulate-bound; dissolved in effluents; Hg also gaseous	Oxidation state; particle size; complexing ligands	Deposition to soil; redox-driven mobilization; long persistence in GW
Volatile organic compounds (VOCs)/solvents (Benzene, toluene, ethylbenzene, xylene—BTEX, chlorinated ethenes)	Degreasing, petrochemical, storage losses	Gaseous; non-aqueous phase liquid (NAPL) in spills	Volatility; density; miscibility; Henry's constant	Air exposure + vadose transport; plume formation in aquifers
Semi-volatile organic compounds (SVOCs)/Polycyclic aromatic hydrocarbons (PAHs)	Combustion, asphalt, coking, industrial heat	Particle-associated + semi-volatile gas	Soot affinity; volatility; ring structure	Atmospheric transport/deposition; strong soil sorption; slow leaching
Persistent organics (polychlorinated biphenyls—PCBs, dioxins)	Legacy equipment, combustion byproducts	Particle-associated; semi-volatile gas	Chlorination degree; vapor pressure	"Grasshopper" cycling; soil as long-term reservoir; food-chain transfer
Per-and polyfluoroalkyl substances (PFAS)	Fluoropolymer production, aqueous film-forming foam (AFFF), plating	Aqueous; precursors in air; particles	Chain length; functional group; precursor mix	Soil–GW mobility; long-range aqueous transport; difficult attenuation
Acid/base precursors (SO_x, NO_x, NH_3)	Power generation, nitric/sulfuric processes, fertilizer	Gaseous	Emission temperature; co-emitted oxidants	Drives secondary aerosols; alters soil pH/metal mobility; affects recharge chemistry

2.3. Emission Modes and Release Pathways

Industrial emissions also have various ways of entry into the environment, with different patterns of space and time of entry of pollutants [11,25,26]. The release of the pollutants in concentrated and well-defined forms often occurs in point sources like stacks, vents, and effluent outfalls, and often enables long-range atmospheric transport or direct discharge to soils and waters. Non-point sources such as fugitive emissions, diffuse leaks, and contaminated materials produce more spatially dispersed inputs, which are hard to measure. The emissions can be in the form of steady-state operations, which are constant, or episodic, which relate to maintaining operations, accidents, and process upsets. Such time processes affect how much the environmental systems can buffer, transform, or store the pollutants. Notably, the mode of emission also influences the initial dispersion and dilution, and as a result, the severity of the contacts with atmospheric oxidants, soil matrices, and groundwater flow systems is controlled.

2.4. Initial Transformations at the Source-Environment Interface

The change in the industrial system to an environmental medium is a significant shift in the pollutant cycling. Emissions are frequently subjected to rapid physicochemical changes as exposure to ambient temperature, pressure, and chemical conditions occurs. Hot exhaust gas is cooled and condensed, and encourages the formation of particles and sorption of semi-volatile compounds. The reactive species can be oxidized immediately or hydrolyzed, and speciation can change before much transport has taken place. In the case of liquid and solid wastes, reactions with the soils or surface waters may lead to dissolution, precipitation, or complexation reactions that determine initial mobility. These initial changes often dictate the entry of the pollutants into the atmosphere as gases or particles, the attachment of the pollutant to the soil solids, or the penetration of the pollutant into the underground systems. Accordingly, the source-environment interface is a gatekeeper, which interconnects industrial processes with the rest of the network of coupled

chemical cycles that occur within the atmospheric, pedologic, and groundwater realms [5,13]. The diversity of industrial source terms and their associated early transformation pathways are illustrated in **Figure 2**.

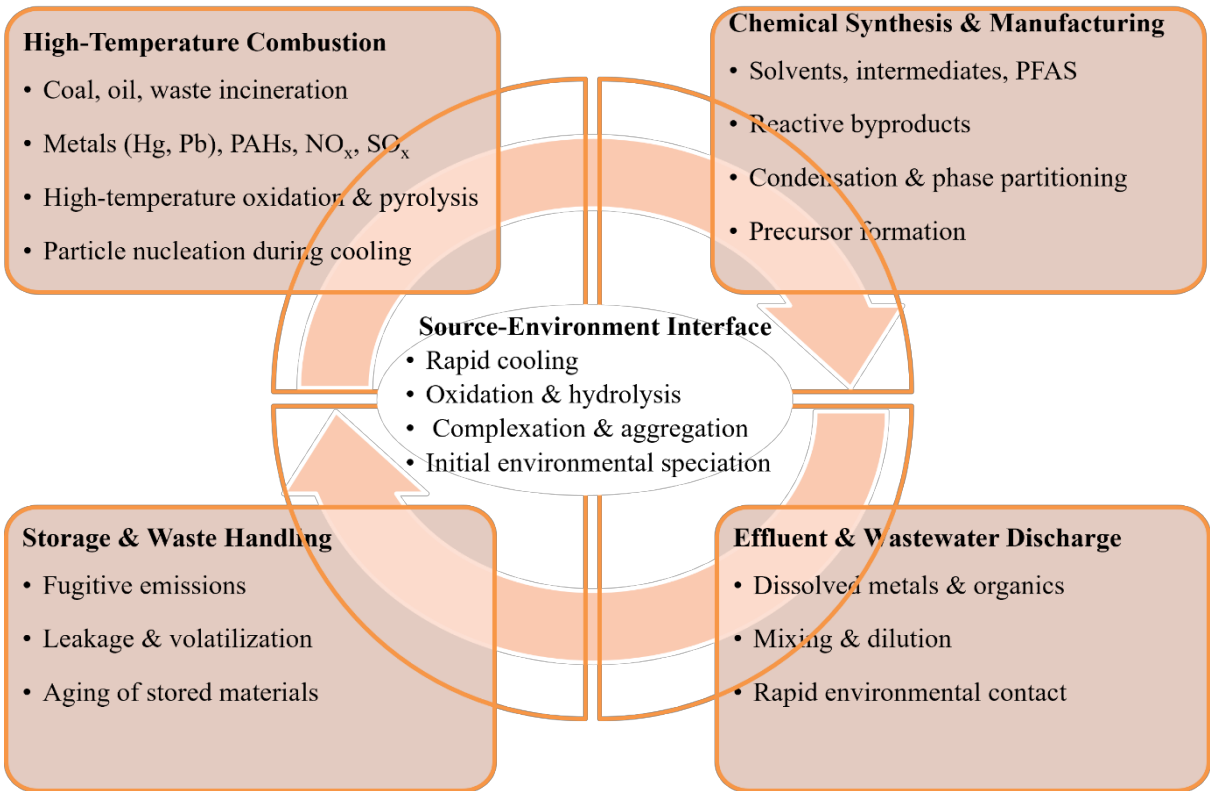

Figure 2. Diversity of industrial source terms and early physicochemical transformations at the source-environment interface.

2.5. Implications for Coupled Environmental Cycling

The variability of the characteristics of source terms leads to a significant amount of heterogeneity in coupled pollutant cycles, even of chemically similar materials. The processes in industries, emission regulations, and operational procedures may generate pollutants that have different environmental patterns and lifetimes. This variability makes it difficult to extrapolate pollutant behaviour across regions or sectors, but it also offers possibilities for specific action on the source. Explicitly taking into account source-term properties and early transformations, cross-media transfers can be more anticipated, and long-term persistence and receptor exposure are better anticipated. In this respect, the source term can be regarded as the primary requirement of coupled chemical cycling, with industrial design and functioning being directly correlated with environmental and human health outcomes [11,27].

3. Atmospheric Chemical Cycling and Intermediate Transfer

Industrial pollutants emitted by anthropogenic sources are transported by the atmosphere and react in the atmosphere [28]. After being released, contaminants are immediately exposed to physical dispersion and chemical transformation processes that dictate their residence, spatial distribution, and shape on deposition to both the land and water surfaces. In coupled chemical cycles, atmospheric processes are central, both in connecting the sources of industry with the soils and groundwater by intermediate transfer and also in facilitating the redistribution of emissions over long distances, dissociating the local effects of emissions from the global effects. Knowledge of atmospheric cycling is thus vital to track the pathways of pollutants from reactors through receptors.

3.1. Gas-Particle Partitioning and Atmospheric Processing

Most industrial pollutants are present in the atmosphere both in gaseous and particulate-linked forms, and the allocation depends on temperature, chemical composition, and aerosol features of the atmosphere [25]. Semi-volatile organic species and some metal species interact dynamically to change phases, affect atmospheric lifetime, and transport potential. Pollutants that are particle-bound have a tendency to be more easily transported over long distances and can also be deposited in different ways than gaseous species. Pollutants are also altered by the atmospheric processing, which includes oxidation, photolysis, and heterogeneous reactions occurring on the surfaces of the particles. This may be done to cause polarization, change the structure of the molecule, or produce secondary products, which have different toxicological and environmental characteristics. Accordingly, the atmosphere will not only carry with it industrial pollutants, but actively redefine their chemical form before intermedia transfer.

3.2. Long-Range Transport and Spatial Redistribution

Atmospheric circulation allows industrial pollutants to travel long distances, way beyond their sources of origin, and thus contributes to contamination of regions and the whole world. Stable gaseous compounds and fine particles can stay for days and weeks, and be transported across national and continental borders [29]. This intercontinental flow combines emissions of various sources and puts remote ecosystems and populations in contact with industrial pollutants. Atmospheric transport efficiency is determined by the meteorological conditions, size of the particle, and chemical stability, as well as the interaction with the clouds and radiation. Long-range transport in the context of coupled cycles increases the spatial scale of soil and groundwater loading and basically connects remote industrialized areas by a common atmospheric route. Major atmospheric processing pathways and their role in intermedia transfer to soils and groundwater are depicted in **Figure 3**.

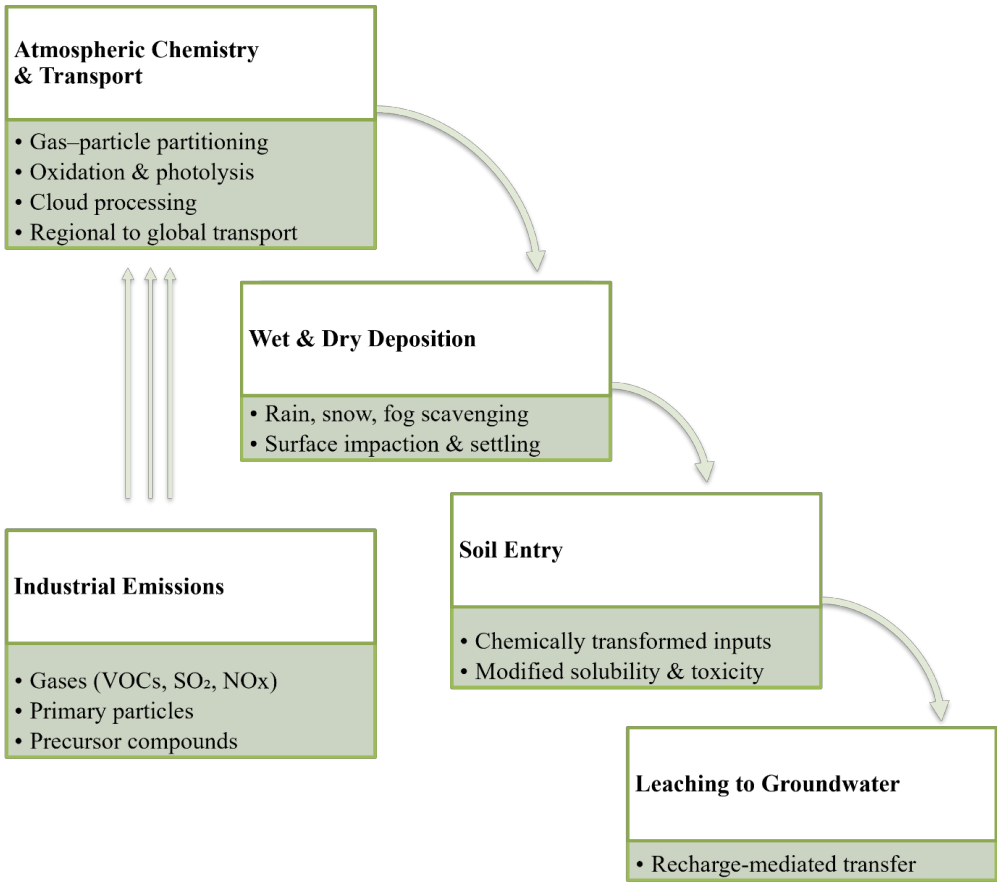

Figure 3. Atmospheric processing, transport, and intermedia transfer pathways connecting emissions to soils and groundwater.

3.3. Wet and Dry Deposition Processes

The major process through which atmospheric contaminants are recycled to soils and waterways is deposition [6,30]. Dry deposition is direct settling or impaction of gases and particles onto surfaces, whereas wet deposition is by way of scavenging of the gases and particles by precipitation. The importance of these processes depends on the properties of pollutants, land cover, and climatic conditions in a relative way. Wet deposition may transport both dissolved and particulate contaminants, and it may be accompanied by other acids or oxidants that may co-transport and affect the further chemistry of soil. Dry deposition, on the contrary, can prefer to settle on vegetation cover and soil surfaces, where later the pollutants can be transported by run-off or infiltration. These deposition routes are important pathways between the atmospheric cycling and the pedologic and groundwater systems. **Table 2** synthesizes important atmospheric processes that control chemical transformation, transport, and transfer of chemicals to terrestrial and subsurface systems.

Table 2. Major atmospheric transformation and intermedia transfer processes governing pollutant delivery to soils and groundwater.

Atmospheric Process	Dominant Controls	What Changes Chemically/Physically	Primary Intermedia Transfer Outcome	Implications For Downstream Soil/GW Behavior
Gas–particle partitioning	Temperature; aerosol organic fraction; humidity	Phase distribution; effective lifetime	Alters deposition efficiency and transport distance	Particle-bound forms may deposit efficiently; gas forms can penetrate canopies/soil air
Photochemical oxidation	Sunlight; OH/O_3/NO_3; VOC mix	Functionalization; polarity; toxicity	Formation of more/less reactive products	More polar products can increase aqueous solubility and leaching potential
Heterogeneous surface reactions	Particle acidity; soot/mineral surfaces	Aging; conversion to secondary species	Shifts deposition and reactivity	Can increase hygroscopicity → enhanced wet deposition and soil delivery
Wet deposition scavenging	Precipitation intensity/type; cloud chemistry	Dissolved vs. particulate delivery	Pulsed loading to soils/surface waters	Episodic leaching events; rapid entry to vadose zone during storms
Dry deposition	Surface roughness; vegetation; particle size	Direct surface accumulation	Chronic loading	Builds near-surface reservoirs that can later mobilize via infiltration/erosion
Re-volatilization/resuspension	Temperature; soil moisture; disturbance	Secondary emissions	Returns contaminants to air	Sustains regional burdens even after emission controls

3.4. Re-Volatilization and Secondary Emissions

The fact that atmospheric deposition is not the end of most industrial pollutants. In favorable conditions, deposited contaminants can be reintroduced into the atmosphere via volatilization, resuspension due to winds, or by means of biomass. These secondary emissions can be increased by temperature variation, alteration of soil moisture, and land disruption, thus contributing to the recycling of pollutants between soil and the atmosphere. Bidirectional interactions cause the separation between sources and sinks to be invoked and form a feedback process that has enhanced atmospheric persistence and makes source attribution more difficult. The re-volatilization processes in question are especially applicable to the semi-volatile organic compounds and forms of some metals in the elements, and the dynamic character of the atmospheric-soil interrelation is highlighted [31,32].

3.5. Atmospheric Coupling with Soil and Groundwater Systems

Having a powerful impact on the inputs of pollutants to the soils and groundwater, the atmosphere acts as a unity of the effects of transformation, transport, and deposition. The chemical form that contaminants are deposited in determines their interactions with soil matrices, sorption, mobility, and bioavailability. Subsequently, soil and groundwater mechanisms can regulate the concentrations in the atmosphere via inferential emissions and retarded release. This mutual interaction brings out the atmosphere as both a driver and a reactor in coupled processes of pollutants. These interactions are critical to account for such factors

that contribute to the correct evaluation of the environmental loading, exposure pathways, and long-term effects of industrial emissions on the interrelated environmental systems [5,6].

4. Pedologic Processes and Soil-Pollutant Interactions

Soils are also at the center stage in the concomitant chemical cycling of industrial contaminants as they are both receivers of atmospheric contributions and controllers of subsurface transport. The pedologic environment is located at the boundary of the atmosphere and groundwater and functions to mediate the retention, transformation, and redistribution of contaminants both spatially and across time. A combination of heterogeneous mineralogy, organic matter content, hydrology, and biological activity complicates the behavior of pollutants in the soil, and similar loading conditions lead to highly temporal behavior of pollutants. Therefore, soils may be utilized as long-term sinks, temporary buffers, or secondarily as a part of integrated environmental processes [33,34].

4.1. Sorption and Retention Mechanisms

The early environment of industrial contaminants in soils is determined to a large extent by sorption processes, whether through atmospheric deposition, surface application, or lateral transportation [35,36]. Organic contaminants are more likely to be related to the soil organic matter via hydrophobic reactions, whereas inorganic species, especially metals, are related to the clay minerals, oxides, as well as carbonate phases. These interactions depend on the strength and reversibility of interactions, which are influenced by soil texture, the content of organic carbon in the soil, pH, and ionic composition of soil solutions. Sorption may significantly decrease the contaminant mobility, slowing down their travel to groundwater and decreasing their immediate bioavailability. Sorption is not always permanent; however, the shift in the soil conditions can stabilize the already bound pollutants and remobilize them, allowing their cross-media transfer.

4.2. Redox and pH-Driven Chemical Transformations

It has been found that soils are characterized by steep redox and pH gradients that have a high degree of control over pollutant speciation and reactivity [17,37]. Dynamic redox environments, which are caused by fluctuations in moisture content through precipitation and evapotranspiration, affect the metals and redox-sensitive organic compounds. The reducing environment can cause dissolution of metals, including iron and manganese, releasing the sorbed contaminants into soil porewater, and oxidizing conditions can enhance the equilibrium of precipitation and immobilization. pH changes also have similar effects on weak acid, weak base, and metal cation solubility, complexation, and sorption equilibrium. These geochemical controls connect the atmospheric inputs to and transport through soil to groundwater, transforming the traditional view of soils as passive repositories of information to the role of soil as an active reactor.

4.3. Microbial Mediation and Biogeochemical Cycling

The fact that biological interaction complicate the interaction between soil and pollutants further. There is a broad spectrum of transformation processes catalyzed by microorganisms, such as the biodegradation of organic contaminants and redox transformations of metals and metalloids. Either of the reactions can be used to detoxify the pollutants or produce intermediates, which are more mobile or toxic. Microbial metabolism is strongly linked with the physicochemical conditions of soils, and it reacts to fluctuations in the status of carbon, nutrients, and moisture. Consequently, the transformations of the industrial pollutant through natural biological processes tend to be enhanced or tuned by the biotic ones, placing industrial contaminants into the wider soil biogeochemical chains that link the atmospheric deposition with the groundwater contamination processes [38,39]. The most prevalent soil processes that govern the level of pollutants retained, transformed, and lost to groundwater are summarized in **Table 3**.

Table 3. Pedologic controls on pollutant retention, transformation, and export within coupled environmental systems.

Soil Process/ Domain	Major Controlling Variables	Pollutant Groups Most Affected	Net Effect on Mobility	Coupling to Atmosphere and Groundwater
Sorption to organic matter	Soil organic carbon (SOC) content; black carbon; aging	SVOCs/PAHs, PCBs, many pesticides	Decreases mobility (often strongly)	Creates long-lived reservoirs; can fuel slow leaching + secondary emissions
Mineral sorption/ complexation	Clay content; Fe/Al oxides; pH	Metals, polar organics	Variable; often decreases mobility	Stabilizes or releases with pH shifts; affects dissolved flux to GW
Redox transitions (oxic–anoxic)	Waterlogging; organic carbon; microzones	Metals, chlorinated solvents, nitrate	Can increase or decrease	Reductive dissolution can release sorbed metals; supports anaerobic degradation
Microbial transformation	Electron donors/acceptors; temperature	VOCs/solvents, hydrocarbons, some PFAS precursors	Often decreases (but not always)	Generates daughter products; controls timing of export to vadose zone
Preferential flow/ macropores	Structure; roots; cracking; storms	Dissolved contaminants; colloids	Increases mobility	Fast pathways to vadose zone/aquifer; weakens protective capacity of sorptive matrix
Erosion and dust generation	Disturbance; wind; vegetation	Particle-bound metals, PAHs	Mobilizes solids	Transfers soil-bound contaminants back to air; redistributes hotspots

4.4. Soil Hydrology and Vertical Transport

Water flow within the soils dictates the flow of the dissolved and colloid-associated pollutants to the vadose zone and underlying aquifers. Under specific conditions, infiltration, percolation, and preferential flow pathways may circumvent sorptive soil matrices, increasing the rate of contaminant migration. On the other hand, thick layers with low permeability and retention may cause a high delay in the downward flow, resulting in pollutants being trapped in near-surface layers. The hydrology of the soil is very sensitive to land use, vegetation cover, and climate variability, which, on the other hand, affect the timing of the groundwater loading and its magnitude. These hydrologic controls, these connections, directly cause pedologic processes to be connected to subsurface chemical cycling and long-term exposure dangers [40,41].

4.5. Soils as Secondary Sources in Coupled Systems

In addition to their sink-filtering properties, soils may serve as a secondary source of industrial pollutants to the atmosphere and the groundwater. Disturbance in place of erosion, cultivation, or construction may increase mobilization of contaminated particles, thereby increasing atmospheric resuspension or surface runoff. Those processes that could be affected by thermal and moisture can facilitate volatilization of semi-volatiles, re-exposing the deposited pollutants to the atmosphere. Likewise, gradual leaching imparts contaminants to groundwater over a long period of time. Such feedback emphasizes the dynamic nature of soils in the interaction of chemicals, where past pollution is still present and affects the current and future environmental quality. It is also important to note that soils are dynamic and active participants in pollutant cycles in order to build credible models of industrial contaminants fate, as well as, design effective mitigation and management strategies [42,43].

5. Groundwater Transport and Subsurface Chemical Transformations

The presence of groundwater systems is an important but frequently overlooked element of the linked chemical circulation of industrial contaminants. When the contaminants spread out below the soil profile to the vadose zone and saturated aquifers, they are exposed to physicochemical environments that are significantly different from those at the surface. The low light supply, low oxygen, steady temperatures, and extended residence time favor transformation pathways and transport dynamics that are different from those found in atmospheric and pedologic systems. Consequently, groundwater serves as a long-term storage as well as a time-lagged buffer between the past and present human

and ecological receivers of industrial emissions [44].

5.1. Vadose Zone Processes and Contaminant Entry

The vadose zone is the first point at which industrial contaminants change their location between the soils and the groundwater. In this unsaturated environment, the contaminants can become wet and dry intermittently, the redox conditions are variable, and they interact with mineral surfaces in a complicated way. The dissolved pollutants can be stored by the process of sorption and precipitation, and volatile compounds can be partitioned to soil gas and move horizontally and vertically. Favored movement along fractures, root channels, or macropores may be able to bypass most of the soil matrix, allowing a rapid contaminant transfer to lower levels. Those processes have a very marked impact on the time and scale of groundwater pollution, as well as injecting a great deal of spatial heterogeneity into the distribution of subsurface pollutants [45,46].

5.2. Advective Transport and Dispersion in Aquifers

When the contaminants penetrate the saturated region, groundwater circulation dictates the spatial redistribution of the contaminants. The dissolved contaminants are transported by advection along the hydraulic gradients and dispersed in the long run as contaminant plumes by mechanical dispersion and molecular diffusion. The groundwater movement is slow in comparison with atmospheric conditions, when it takes years or decades to move, yet it can maintain long exposure routes. Further effects on the geometry and rates of migration of the plume are caused by aquifer heterogeneity, such as differences in permeability and porosity. These physical transportation mechanisms define the context in which chemical and biological changes take place, and this eventually dictates the longevity and location of industrial contaminants in the underground systems [47].

5.3. Redox-Driven and Mineral-Mediated Transformations

Reducing environments are common in groundwater environments and often prefer transformation pathways that are not common in surface soils or in the atmosphere [48]. The process of redox reactions of iron, manganese, sulfur, and carbon cycles can change the speciation, mobility, and toxicity of the pollutants present in industries. Metals can be deposited in the form of sulfides or carbonates, and this leads to lower dissolved concentrations, and reductive dissolution of iron oxides can elicit contaminants that were originally sorbed. In the case of organic pollutants, reductive dehalogenation and other anaerobic routes of degradation of parent compounds can be used to convert them into daughter products that have different environmental profiles. Pollutants are fixed in subsurface geochemical matrices in the form of mineral surfaces in aquifers as the reactive sites and as long-term sinks.

5.4. Microbial Processes and Biodegradation

Microbial communities occurring in groundwater are also important in the subsurface chemical cycling; these communities mediate a variety of redox reactions and biodegradation. Despite the fact that in many cases, microbial activity is constrained by nutrient and energy supplies, even very low metabolic rates may have an enormous effect over extended periods of time. Local microorganisms can also evolve to use industrial pollutants as reducing agents or oxidizing agents and promote transformation processes that may weaken or increase contamination. These biological mediation processes are closely linked to the geochemistry and hydrology of groundwater, which support the integrated relationship of physical, chemical, and biological regulation of the fate of pollutants [49,50].

5.5. Groundwater as a Delayed Exposure Pathway

The dynamics of groundwater systems are slow, and give the industrial emissions and the receptor a considerable time lag. The contaminants that were deposited many decades ago can still be found in aquifers and slowly dissipate to the wells, springs, or surface waters and pose long-term risks that cannot be easily predicted and handled. This sluggish reaction to it makes remediation more complex, and regulatory frameworks are problematic in that they emphasize short-term emissions reduction. Groundwater is used in coupled chemical cycles as a pattern of the past industrial activity, as the association between the circumstances of at-

mospheric deposition and soil pollution is connected to the future context of exposure. Use of groundwater as an active and dynamic element of the pollutant cycling is thus critical to the overall assessment and management of this sector when it comes to the comprehension and ecological sustainability of industrial contaminants [51,52].

6. System-Level Coupling, Modeling, and Human-Ecological Receptors

The distributed chemical cycling of industrial pollutants between atmospheric, pedologic, and groundwater systems creates emergent behaviors that cannot be comprehended by studying each of the environmental compartments in isolation. A combination of transport processes, chemical processes, and biological processes gives rise to nonlinear responses, feedback systems, and time lags, which determine the distributions of pollutants and exposure pathways. System-level visions are hence critical to the assimilation of mechanistic knowledge across media and to the association of environmental cycling with the effects on human and ecological receptors [53].

6.1. Cross-Media Coupling and Feedback Mechanisms

Bi-directional fluxes and feedbacks between the atmospheric, soil, and groundwater systems determine couplings between the systems at different scales [54,55]. Through atmospheric deposition, transformed pollutants are deposited in the soils, and the soils control the later division of retention, groundwater re-emission, or release into the atmosphere. Groundwater systems, in their turn, are long-term storage facilities, which over time releases the contaminants to the surface waters or wells, which may reintroduce the contaminants back to the surface and atmospheric cycles. The change of land-use, remediation processes, or extreme weather events may break such equilibria and mobilize hitherto sequestered contaminants and shift the pathways of transport. These kinds of feedback mechanisms point out the fact that industrial pollution should be regarded as an active system instead of a series of discrete transfers.

6.2. Integrated Modeling Approaches

Various integrated models have been created to be able to capture the complexity of coupled chemical cycles. The multimedia fate models are used to associate emissions with concentrations in the compartments of air, soil, and water using physicochemical properties and transfer coefficients. Further models combine atmospheric chemistry models and hydrological models, and reactive transport models to model spatially explicit pollutant cycling. The models can be used to ask scenario-based questions, such as the long-term impacts of emission reductions and land management in the case of climate change. Nevertheless, model uncertainty is still large because of the drawbacks of parameterization, integration of scale, and biological processes. Further development of integrated models is essential in order to transform scientific knowledge into useful decision-making instruments [56,57]. The frameworks of representative modeling between cross-media pollutant cycling and receptor-relevant outcomes are summarized in **Table 4**.

Table 4. Modeling approaches for coupled chemical cycling and their relevance to receptor-oriented assessment.

Approach	Typical Spatial/ Temporal Scale	Core Linkages Represented	Data Requirements	Receptor-Relevant Outputs
Multimedia fate models (compartmental)	Regional; days–years	Air ↔ soil ↔ water via transfer coefficients	Emissions; partitioning constants; deposition rates	Cross-media concentrations; dominant pathways; screening-level risk
Coupled atmospheric chemistry–transport + deposition	Regional–global; hours–weeks	Transformation + deposition fields	Emissions speciation; meteorology; chemical mechanisms	Deposition flux maps; source attribution explaining soil loading
Reactive transport models (vadose + aquifer)	Site–watershed; years–decades	Advection/dispersion + reactions	Hydrostratigraphy; Kd/ kinetics; redox; biodegradation	Plume evolution; travel times to wells; persistence/attenuation estimates
Integrated watershed/hydro-biogeochemical models	Catchment; seasons–decades	Recharge + runoff + soil reactions	Land use; hydrology; soil maps; climate	Time-varying loading to GW/surface water; management scenario outcomes
Exposure pathway models (link to receptors)	Household–population; days–lifetime	Media → intake (air, water, food, soil)	Concentrations; consumption/behavior; bioaccumulation	Dose distributions; sensitive subpopulations; risk drivers

6.3. Temporal Dynamics and Legacy Contamination

Decoupling between the timing of emissions and the timing of exposure is one of the characteristics of coupled pollutant systems. Whereas atmospheric concentrations can be quick to react to changes in industrial activity, soils and groundwater have the ability to hold the contaminants over a long period of time, thus releasing them over decades. The contamination in this legacy makes it difficult to assign any observed exposures to current sources or historic sources, and makes it difficult to implement regulatory frameworks that have short-term compliance goals. The system-level analysis, which is explicit in terms of storage, delayed transport, and transformation, is thus required to effectively estimate risks and to develop remediation plans aimed at curbing long-term environmental liability [58].

6.4. Pathways to Human and Ecological Receptors

The result of coupled chemical cycles is human and ecological receptors via various exposure pathways [59]. Airborne pollution, water and food contamination, as well as dermal contact with soils, are all products of cross-media cycling. Terrestrial and aquatic organisms are ecological receptors that undergo bioaccumulation and biotrophic transfer mechanisms, which are sensitive to environmental changes due to changes in pollutant speciation and bioavailability. The rationale that drives the development of these pathways is that the nature of the pathways makes it important to adopt receptor-oriented views that bridge the differences between environmental concentrations and biologically relevant doses in a system approach model.

6.5. Implications for Risk Assessment and Management

The acknowledgment of the intertwined character of the industrial pollutants cycling has some significant implications concerning risk assessment, regulation, and environmental controls. Compartment-specific standards can be underwhelming of cumulative or delayed risks that emerge out of cross-media interactions. Comprehensive tests that take into account the interactions between the atmosphere, soil, and groundwater are more appropriate to represent the overall exposure and provide the leverage point to conduct an intervention. Through harmonization of industrial design, emission management, land management, and groundwater protection in an integrated context, system-level strategies provide a means of achieving a more viable and sustainable management of industrial pollutants between reactors and receptors [18,60].

7. Conclusions

Pollutants in industries do not exhibit straight and narrow paths of emission-exposure. They are not isolated, but, in fact, are involved in coupled chemical cycles, which connect industrial reactors to human and ecological receptors, through a network of interacting physical, chemical, and biological processes. The present review has presented an integration of recent knowledge on these coupled pathways, with the focus being on the fact that cross-media interactions and feedback control the fate and impact of pollutants as much as source strength does.

When a generation occurs, the first physicochemical peculiarities of the pollutants are determined by industrial processes, which limit their further action. These substances are redistributed in the atmosphere; over large spatial units, and their chemical form is changed before deposition. The next operation is that soils are dynamic interfaces that combine both atmospheric inputs and control mobility and mediate transformation by forming a geochemical and biological system. Groundwater systems also prolong the temporal range of industrial contamination by storing and emitting the contaminants over time at a slow rate through the delayed exposure routes. Collectively, these compartments constitute a network structure whereby pollutants can be stored, converted, and re-released to receptors several times.

Another key finding of this synthesis is that it is crucial to decouple emissions and impacts in time. Although the atmospheric reactions to industrial controls might be quick, pedologic and groundwater reservoirs can continue the history of past contamination. This continuity makes the evaluation of exposure difficult, source attribution harder, and the regulation methods centered on present emission levels. No system-level point further brings

about nonlinearities, such that a disturbance like land-use change, climate variability, or remediation activities can switch over a dominant pathway, and challenge what was previously viewed as a constant concentration of contaminants to mobilize.

The developments in integrated modeling, environmental tracing, and monitoring have just started to shed light on these complexities, but there are still huge knowledge gaps. A better representation of the processes of soil and groundwater, improved quantification of the bidirectional fluxes, and the enhancement of the integration of the biological transformations are required to minimize the uncertainty of the analysis of coupled systems. These gaps will be filled by interdisciplinary knowledge to address the gap between atmospheric science, soil science, hydrogeology, and exposure science.

As a management issue, the importance of viewing industrial pollutants as parts of the coupled chemical cycles is significant. The mitigation measures should go beyond emission reduction to include long-term storage, delayed release, and transfer across media. Development of less environmentally persistent industrial systems, integration of remediation, system-level processes, and integration of legacy contamination in risk frameworks are all important measures to sustainable pollution control.

To sum up, the shift to integrated, cross-media views and away from the compartmentalized ones will establish a more realistic context for how to comprehend and address the problem of industrial pollution. Connecting reactors to receptors with the explicit help of coupled atmospheric, pedologic, and groundwater processes, this framework provides a direction for better environmental protection and informed design of industry in the increasingly intricate and interconnected world.

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