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SOIL PEDOGENESIS IN THE ANTHROPOCENE: A REVIEW OF MODERN APPROACHES AND EMERGING CHALLENGES

Luxmi Kant Tripathi*, Sunil Kumar and Sachchida Nand Singh

College of Agriculture Sciences (ICAR-Accredited), Teerthanker Mahaveer University, Moradabad, U.P. – 244001, India

*Corresponding author E-mail: tripathicsa@gmail.com

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ABSTRACT

The Anthropocene, a proposed geological epoch defined by humanity's overwhelming impact on Earth's systems, has fundamentally altered the trajectory of soil formation (pedogenesis). This review provides a comprehensive synthesis of the current understanding of how human activities are reshaping soil-forming processes, leading to the development of novel soil types and posing unprecedented challenges to global soil security and ecosystem services. We critically examine the fundamental drivers of pedogenesis in the Anthropocene, including intensive agriculture, urbanization, industrial pollution, mining, and anthropogenic climate change. These drivers introduce new parent materials, drastically alter soil horizons, modify biogeochemical cycles at planetary scales, and accelerate erosion and formation rates far beyond natural geological timescales. The paper provides a detailed overview of the modern analytical toolbox used to characterize these anthropogenically-influenced soils. This includes advanced spectroscopic methods (e.g., FTIR, XRF, Synchrotron-XAS), high-resolution remote and proximal sensing, stable and radioactive isotopic tracers, and a suite of 'omics' technologies (metagenomics, proteomics) for analyzing the soil microbiome's response to anthropogenic stress. These tools enable a nuanced, mechanistic understanding of the complex interactions between human-made materials and natural soil components. We then delve into the most pressing emerging challenges, with a particular focus on the pedogenesis and management of Technosols soils dominated by artificial materials and the pervasive, insidious issue of emerging contaminants. These include microplastics, pharmaceuticals and personal care products (PPCPs), engineered nanomaterials (ENMs), and per- and polyfluoroalkyl substances (PFAS), the "forever chemicals." The long-term impacts of these contaminants on soil structure, function, health, and their potential transfer into the food chain are critically evaluated. Finally, this review highlights the critical need for an integrated, interdisciplinary, and forward-looking approach to soil science in the Anthropocene. Understanding these new pedogenic pathways is not merely an academic exercise but an urgent necessity for developing sustainable land management strategies, ensuring global food and water security, remediating contaminated landscapes, and mitigating environmental degradation on a human-dominated planet. We conclude by outlining key research gaps and future directions, emphasizing the urgency of adapting pedological theory and practice to address the profound complexities of a rapidly changing Earth.

***Keywords*:** Pedogenesis, Anthropocene, Technosols, Soil Contamination, Soil Security, Modern Analytical Techniques, Microplastics, PFAS, Agricultural Soils, Urban Soils, Sustainable Land Management.

Introduction

Soil, the fragile, living skin of the Earth, is arguably the most critical and complex natural resource for human civilization. It is the foundation of our food systems, the planet's largest active terrestrial carbon store, a vast reservoir of biodiversity, and the primary filter for our freshwater supplies (Amundson *et al.*, 2015). The formation of this vital resource, a process known as pedogenesis, has traditionally been understood through the elegant and enduring framework of Hans Jenny's five state factors: climate, organisms, relief (topography), parent material, and time (Jenny, 1941). This classical model has been the bedrock of soil science for nearly a century, eloquently describing the slow, incremental development of soil profiles and their associated horizons over geological timescales, from centuries to millennia. It portrays a world where soils evolve in a state of dynamic equilibrium with their natural environment.

However, the last century has witnessed a profound and accelerating shift in the state of our planet. The advent of the Anthropocene, a new geological epoch proposed to mark the end of the Holocene, acknowledges that humanity has become a geological superpower, a primary driver of planetary-scale change (Crutzen, 2002; Waters *et al.*, 2016; Zalasiewicz *et al.*, 2017). Human activities he sheer scale of our agriculture, the explosive growth of our cities, the global reach of our industries, and our alteration of the global climate are now so pervasive and profound that they are leaving an indelible and globally synchronous signature in the geological record. Nowhere is this signature more apparent than in the soil itself. Humanity has forcefully inserted itself into Jenny's equation, not merely as another organism, but as a sixth, dominant pedogenic factor that modifies, overrides, and often completely replaces the natural factors (Richter & Yaalon, 2012).

The rates of change are staggering. Human-induced soil erosion from agriculture now moves sediment at a pace that far exceeds the combined effect of all natural processes (Montgomery, 2007). We have doubled the global flux of reactive nitrogen through the Haber-Bosch process, fundamentally altering soil chemistry and nutrient cycles (Galloway *et al.*, 2008). We are creating entirely new parent materials in the form of urban fill, mine spoils, and landfill waste, from which entirely new soils Technosols are forming on human timescales of years and decades (Scalenghe & Marsan, 2009). The soils of the Anthropocene are thus fundamentally different from their Holocene predecessors. They are often complex hybrid systems, or 'anthro-natural' systems, where human artifacts and contaminants are inextricably mixed with natural minerals and organic matter. Their profiles tell stories not of slow ecological succession, but of abrupt land-use change, industrial history, and waste disposal.

This paradigm shift presents both immense challenges and critical research opportunities for soil science. A failure to understand and manage these new pedogenic trajectories will have dire consequences for food security, human health, and environmental quality. The traditional view of soil as a purely natural body is no longer tenable. We must now conceptualize soils as dynamic entities co-evolving with human societies. This review paper aims to provide a comprehensive, multi-faceted synthesis of the state of knowledge on soil pedogenesis in the Anthropocene. We will begin by systematically exploring how major human activities are redefining the classical soil-forming factors and driving novel pedogenic processes. We will then survey the advanced analytical toolbox that is enabling scientists to characterize these complex, human-altered soils with unprecedented detail. Following this, we will delve into the major emerging challenges that will define the future of soil science, including the classification and management of Technosols and the pervasive threat of a new generation of contaminants like microplastics and "forever chemicals." Finally, we will conclude by outlining the future directions for research, policy, and management, emphasizing the need for an integrated, forward-looking approach to soil science that can meet the demands of a rapidly changing world. The central thesis of this review is that the Anthropocene demands nothing less than a fundamental expansion of pedological theory and practice, one that fully incorporates humanity as the most powerful and transformative force in the creation and evolution of Earth's soils.

The Human Factor: Redefining Pedogenesis in the Anthropocene

The classical equation of soil formation, S = f(cl, o, r, p, t), must now be rewritten as S = f(cl, o, r, p, t, h), where 'h' represents the pervasive and often dominant influence of human activities. This human factor does not act in isolation; it interacts with, modifies, and frequently overwhelms the original five factors. This section provides a detailed examination of how the primary drivers of the Anthropocene agriculture, urbanization, industry, and climate change are fundamentally altering the processes and products of pedogenesis.

Agricultural Pedogenesis: The Global Experiment in Soil Manipulation

Agriculture represents humanity's oldest and most extensive direct manipulation of soil. From the earliest Neolithic farmers to modern industrial agribusiness, we have been engaged in a global-scale experiment in soil management, with profound consequences for pedogenesis.

Physical Restructuring: The Plough Layer, Compaction, and Accelerated Erosion

The most visible signature of agriculture is the physical homogenization of the topsoil. Conventional tillage, particularly the use of the mold board plough, inverts and mixes the upper 20-30 cm of the soil profile. This process, known as *agropedoturbation*, obliterates the naturally formed O, A, and E horizons, blending them into a single, morphologically uniform layer known as the Ap (plough) horizon (Kravchenko & Guber, 2017). This layer is characterized by a sharp, linear boundary with the underlying, undisturbed B horizon. While tillage temporarily decreases bulk density and increases porosity, the long-term consequences are often detrimental. The repeated trafficking of heavy machinery, often when the soil is wet, exerts immense pressure, leading to the formation of a dense, compacted layer known as a *plough pan* or *traffic pan* at the base of the Ap horizon. This compacted zone has a high bulk density, low porosity, and platy structure, which severely impedes root penetration, water infiltration, and gas exchange, effectively creating an artificial barrier within the soil profile (Hamza & Anderson, 2005).

Perhaps the most damaging physical impact of agriculture is the dramatic acceleration of soil erosion. By removing the protective canopy of natural vegetation and disrupting soil aggregates through tillage, agricultural practices leave the soil surface vulnerable to the kinetic energy of raindrops (splash erosion) and the shear stress of overland flow (sheet and rill erosion) and wind. Global estimates suggest that cropland erosion occurs at rates 10 to 100 times greater than the natural rates of soil formation (Montgomery, 2007). This "truncated pedogenesis" strips away the most fertile, organic-rich topsoil, exposing the less fertile subsoil (B horizons) or even parent material (C horizons) to the surface. The eroded sediment, enriched with nutrients and pesticides, is transported downslope and downstream, where it accumulates in depositional settings like foot slopes, floodplains, and reservoirs. This process, termed *colluviation* or *alluviation*, buries pre-existing soils and initiates new pedogenesis on the fresh deposits, creating complex "aggraded" soil profiles that serve as a clear stratigraphic marker of the Anthropocene (Vanwalleghem *et al.*, 2017).

Chemical Re-engineering: The Legacy of Fertilizers, Amendments, and Pesticides

Modern agriculture is powered by massive inputs of synthetic chemicals that have fundamentally re-engineered soil biogeochemistry. The Haber-Bosch process, which synthesizes reactive nitrogen (N) from atmospheric N_2, is arguably one of the most significant anthropogenic alterations to a global biogeochemical cycle. The application of N fertilizers (e.g., urea, ammonium nitrate) has led to a doubling of N inputs to terrestrial ecosystems (Galloway *et al.*, 2008). While boosting yields, this has a significant acidifying effect. The microbial nitrification of ammonium (NH_4^+) to nitrate (NO_3^-) releases hydrogen ions (H^+), systematically lowering soil pH over time. This process is exacerbated by the uptake of cations by crops and the leaching of nitrate. A meta-analysis of Chinese croplands, for instance, revealed significant acidification over just a few decades, with profound implications for nutrient availability and aluminum toxicity (Guo *et al.*, 2010).

Phosphorus (P), mined from finite rock phosphate reserves, is another cornerstone of modern fertilization. Unlike nitrogen, P is relatively immobile in most soils, binding strongly to iron and aluminum oxides in acid soils and calcium minerals in alkaline soils. Decades of over-application have led to the accumulation of a massive "legacy P" reservoir in the topsoil of many agricultural regions (Sattari *et al.*, 2012). This anthropogenic P enrichment creates a distinct vertical chemical gradient that is a hallmark of agricultural pedogenesis. While this legacy P can be a future resource, it also poses a long-term risk of eutrophication to adjacent water bodies if soil P saturation capacity is exceeded.

Irrigation, essential for agriculture in arid and semi-arid regions, also drives a distinct pedogenic process: *salinization* and *sodification*. All irrigation water contains dissolved salts. When this water is applied to fields and evaporates, the salts are left behind, gradually accumulating in the root zone. Over time, the total dissolved solids (TDS) can reach levels that are toxic to crops. If the irrigation water has a high proportion of sodium (Na^+) relative to calcium (Ca^{2+}) and magnesium (Mg^{2+}), sodification can occur. The Na^+ displaces Ca^{2+} and Mg^{2+} on the clay exchange sites, causing the clay particles to disperse, destroying soil structure, and rendering the soil impermeable and difficult to cultivate (Qadir *et al.*, 2014).

Finally, the vast arsenal of synthetic pesticides (herbicides, insecticides, fungicides) used in modern agriculture introduces complex and often persistent organic molecules into the soil. While targeting pests, these compounds can have non-target effects on the vast diversity of soil organisms, from beneficial microbes to earthworms. The persistence of these compounds, measured by their half-life, varies from days to decades. Some, like the organochlorine DDT, are notoriously persistent and can bioaccumulate in food webs, while their breakdown products can sometimes be even more toxic than the parent compound (Arias-Estévez *et al.*, 2008).

Urban and Industrial Pedogenesis: The Genesis of Technosols

Urbanization is one of the most extreme and irreversible forms of land transformation. It involves the complete destruction of pre-existing soil profiles and their replacement with a complex, heterogeneous mixture of natural and artificial materials. The soils that form in, on, and from these materials are known as Technosols, the quintessential soils of the Anthropocene (IUSS Working Group WRB, 2015).

Novel Parent Materials and Artificial Stratigraphy

The parent materials of urban soils, often termed "made ground," "urban fill," or "anthropic deposits," are a chaotic assemblage of human-transported substances. They can include construction and demolition debris (concrete, bricks, mortar, glass, asphalt), industrial byproducts (fly ash from power plants, slag from smelters, dredge spoils from harbors), municipal solid waste, and imported soil, sand, and gravel (Ford *et al.*, 2014). These materials are deposited in layers, creating a highly complex and discontinuous stratigraphy that bears no resemblance to natural soil horizons. A typical urban soil profile might consist of a thin layer of topsoil over a thick layer of brick rubble, followed by a lens of coal ash, overlying compacted clay fill. These sharp boundaries between layers, often with contrasting physical and chemical properties, disrupt the vertical flow of water, air, and nutrients, and create formidable barriers to root growth. This artificial layering is a defining feature of urban pedogenesis.

Extreme Chemical Environments and Pervasive Contamination

The chemical environment of Technosols is often far outside the range of natural soils. The presence of large amounts of cement, concrete, and mortar, which contain calcium carbonate and calcium hydroxide, can lead to a process of *urban carbonation*. These materials react with atmospheric CO_2, creating a strong buffering system that maintains a very high pH (often > 8.5) and high electrical conductivity (Lehmann & Stahr, 2007). Conversely, Technosols formed from industrial wastes like mine spoils can be extremely acidic.

The most defining chemical characteristic of urban and industrial soils, however, is the prevalence of contamination. These soils act as long-term sinks for pollutants released from traffic, industry, and historical activities. Heavy metals are a primary concern. Lead (Pb) from legacy leaded gasoline and paint, zinc (Zn) and copper (Cu) from traffic (tire wear, brake dust) and industrial emissions, and cadmium (Cd) from industrial processes and waste are commonly found at concentrations that far exceed regulatory guidelines and pose significant risks to human health, particularly for children (Mielke & Reagan, 1998). Organic contaminants are also ubiquitous. Polycyclic aromatic hydrocarbons (PAHs), products of incomplete combustion of fossil fuels, are common along roadsides and in industrial areas. Polychlorinated biphenyls (PCBs), once used in electrical transformers, and dioxins, byproducts of industrial processes and incineration, are highly persistent and toxic compounds that can be found at legacy industrial sites (Lohmann *et al.*, 2007). This pervasive "legacy contamination" is a permanent feature of the pedogenesis of these soils, influencing all aspects of their function and management.

Mining and Its Pedogenic Legacy: The Creation of Anthrogeomorphic Landscapes

Mining operations represent one of the most extreme forms of direct human geomorphic agency. The excavation of open-pit mines and the practice of mountaintop removal involve the stripping and movement of colossal volumes of rock and soil (overburden). This material is deposited in vast spoil heaps and valley fills, creating entirely new, human-designed landforms. Pedogenesis on these substrates begins from a state of extreme disturbance.

The parent material of mine spoils is often physically and chemically hostile to life. It is typically coarse, rocky, and devoid of the fine earth fraction needed to retain water and nutrients. It lacks organic matter and the microbial communities necessary to initiate nutrient cycling. The most severe chemical challenge often arises from the exposure of sulfide minerals, particularly pyrite (FeS_2), which is common in coal and metal ore deposits. In the presence of air and water, pyrite oxidizes to form sulfuric acid and dissolved iron, a process known as *acid mine drainage* (AMD) or *acid rock drainage* (ARD) (Akcil & Koldas, 2006). This process, often accelerated by iron-oxidizing bacteria like *Acidithiobacillus ferrooxidans*, can drive the pH of the spoil material and associated drainage water down to extremely low levels ($pH < 3$). This extreme acidity, coupled with the high concentrations of soluble toxic metals (Al, Mn, Cu, Zn) that are mobilized under these conditions, creates an environment so toxic that it can remain barren of vegetation for centuries, a state of severely arrested pedogenesis.

Anthropogenic Climate Change as a Global Pedogenic Modifier

Superimposed on all these direct land-use impacts is the overarching, indirect influence of anthropogenic climate change. By altering the global energy balance, we are fundamentally changing the boundary conditions for soil formation everywhere.

- **Temperature and Moisture Regimes:** Rising global temperatures accelerate the rates of nearly all biogeochemical processes, including mineral weathering and, most critically, the decomposition of soil organic matter (SOM). This has led to concerns that soils could switch from being a net carbon sink to a net source, creating a positive feedback loop that accelerates climate change (Crowther *et al.*, 2016). Changes in precipitation patterns amount, frequency, and intensity directly alter soil moisture regimes, the master variable controlling soil life. More intense rainfall events lead to increased erosion, while longer and more severe droughts can lead to vegetation loss and desertification.
- **Permafrost Thaw:** In the Arctic and Boreal regions, rising temperatures are causing the widespread thawing of permafrost ground that has been frozen for millennia. This process, known as *thermokarst*, is profoundly altering the pedogenesis of these cold-region soils (Gelisols). As the ice-rich ground thaws, it can collapse, creating a chaotic landscape of hummocks and depressions. More importantly, the thaw exposes vast stores of previously frozen organic carbon estimated to be twice the amount of carbon currently in the atmosphere to microbial decomposition. These releases large quantities of CO_2 and methane (CH_4) into the atmosphere, representing another dangerous climate feedback loop (Schuur *et al.*, 2015).
- **Sea-Level Rise:** In low-lying coastal zones, rising sea levels driven by thermal expansion of the oceans and melting ice sheets are causing the progressive inundation of terrestrial soils. The intrusion of seawater into coastal aquifers and onto the land surface leads to rapid *salinization*, converting freshwater wetlands and productive agricultural soils into salt marshes or barren mudflats. This represents a rapid, human-driven transgression of marine conditions onto terrestrial landscapes, forcing a complete and often irreversible shift in pedogenic pathways.

Table 1: Summary of Anthropogenic Impacts on Pedogenic Processes

Human Activity	Primary Driver	Impact on Soil-Forming Factors	Key Pedogenic Processes	Resulting Soil Characteristics /Horizons	References
Agriculture	Tillage, Fertilization, Irrigation, Machinery	**Organisms:** Reduced biodiversity. **Topography:** Leveling, terracing. **Parent Material:** Homogenization.	**Agropedoturbation**, accelerated erosion (truncation), compaction, chemical enrichment (eutrophication), acidification, salinization/sodification.	**Ap horizon**, plough pan (Btx), colluvial deposits, nutrient imbalances, altered pH, legacy P accumulation.	Montgomery (2007), Guo *et al.* (2010), Hamza & Anderson (2005)
Urbanization	Construction, Filling, Sealing	**Parent Material:** Replaced with artificial materials. **Topography:** Drastic alteration. **Organisms:** Urban heat island. **Time:** Reset/compressed.	**Technosol formation**, stratification of fill, extreme compaction, hydrologic disruption (sealing), urban carbonation, contamination.	**Technic horizons**, presence of artifacts, high pH, high bulk density, legacy contamination (Pb, PAHs).	Scalenghe & Marsan (2009), Lehmann & Stahr (2007)
Industrial/Mining	Waste Disposal, Excavation	**Parent Material:** Replaced with spoils, slag, ash. **Topography:** New landforms (spoil heaps).	**Extreme acidification** (AMD/ARD), intense metal leaching, arrested pedogenesis, extreme alkalinization.	**Sulfuric horizons** ($pH<3.5$), toxic levels of heavy metals, devoid of organic matter, poor structure.	Akcil & Koldas (2006)
Climate Change	GHG Emissions	**Climate:** Increased temperature, altered precipitation, higher CO_2.	**Accelerated decomposition**, permafrost thaw (cryoturbation), enhanced weathering, increased erosion from extreme events, coastal salinization.	Thinner O horizons, deeper weathering, loss of permafrost, development of saline horizons in coastal soils.	Crowther *et al.* (2016), Schuur *et al.* (2015)

Modern Approaches to Studying Anthropocene Soils

The unprecedented complexity, heterogeneity, and novelty of Anthropocene soils demand an analytical toolbox that extends far beyond traditional methods of spade, auger, and wet chemistry. This section reviews the advanced techniques that are enabling a more mechanistic and quantitative understanding of these human-modified systems.

High-Resolution Remote and Proximal Sensing: Seeing the Soil at Scale

Satellite and Aerial Remote Sensing

Remote sensing from spaceborne and airborne platforms provides the synoptic view necessary to assess the large-scale impacts of human activities on soils. While traditional multispectral sensors like Landsat have been workhorses for monitoring land-use change for decades, the advent of hyperspectral imaging (or imaging spectroscopy) has been a game-changer. These sensors capture data in hundreds of contiguous, narrow spectral bands, producing a detailed reflectance spectrum for each pixel. Specific absorption features within this spectrum, caused by the vibration and stretching of molecular bonds, act as fingerprints for different soil constituents. For example, absorption features around 1400, 1900, and 2200 nm are related to clay minerals and water, while broader features across the visible and near-infrared are indicative of soil organic matter and iron oxides (Ben-Dor *et al*., 2009). This allows for the quantitative mapping of these key soil properties across entire landscapes, enabling, for instance, the assessment of soil carbon stocks or the identification of areas with severe clay loss due to erosion.

Proximal Soil Sensing (PSS)

PSS technologies bridge the critical scale gap between satellite pixels and laboratory samples. They involve deploying sensors on or near the soil surface, often mounted on vehicles for rapid, "on-the-go" mapping. This approach is central to the field of precision agriculture and is increasingly used for environmental site assessment. Key PSS technologies include:

- **Visible and Near-Infrared (Vis-NIR) Spectroscopy:** Portable Vis-NIR spectrometers are perhaps the most powerful PSS tool. They are rapid, non-destructive, and can predict a wide range of soil properties (e.g., carbon, nitrogen, clay, moisture, pH) from a single spectrum through the use of multivariate statistical models (chemometrics). This allows for the creation of high-resolution 3D maps of soil properties, revealing the fine-scale heterogeneity created by agricultural management or contaminant plumes (Viscarra Rossel *et al*., 2011).
- **X-ray Fluorescence (XRF) Spectroscopy:** Portable XRF (pXRF) analyzers use an X-ray source to excite atoms in the soil, which then fluoresce at energies characteristic of each element. This provides a rapid, in-situ measurement of the total elemental composition of the soil. Its primary application is in the mapping of heavy metal contamination in urban and industrial sites, allowing for the rapid delineation of hotspots and guiding more targeted sampling and remediation efforts (Weindorf *et al*., 2014).
- **Electromagnetic Induction (EMI):** EMI sensors work by inducing a primary magnetic field in the soil, which in turn creates eddy currents that generate a secondary magnetic field. The strength of this secondary field is a measure of the soil's apparent electrical conductivity (ECa). ECa is a complex property influenced by clay content and mineralogy, water content, and salinity. EMI surveys are therefore excellent for mapping variations in soil texture, locating compacted zones, and tracking the movement of saline groundwater or contaminant plumes (Corwin & Lesch, 2005).

Advanced Spectroscopic and Microscopic Techniques: Probing Molecular-Scale Mechanisms

To truly understand the novel biogeochemical processes occurring in Anthropocene soils, we must investigate them at the molecular and atomic scale.

- **Synchrotron-Based Spectroscopy:** Synchrotron light sources are particle accelerators that produce X-ray beams billions of times brighter than those from laboratory sources. This allows for a suite of techniques that can probe the chemical environment of specific elements within a complex matrix like soil. X-ray Absorption Spectroscopy (XAS), which includes X-ray Absorption Near Edge Structure (XANES) and Extended X-ray Absorption Fine Structure (EXAFS), is particularly powerful. It can determine the *speciation* of an element its oxidation state and the specific atoms it is bonded to. This is critical for assessing risk, as the toxicity and mobility of a contaminant like arsenic or chromium depend entirely on its chemical form. For example, XAS has been used to show that lead from gasoline is often bound within highly stable iron oxide minerals in roadside soils, rendering it less bioavailable than previously thought (Manceau *et al.*, 2002).

- **Fourier Transform Infrared (FTIR) Spectroscopy:** FTIR spectroscopy is used to identify the functional groups (e.g., C-H, O-H, C=O) present in organic matter. It is a valuable tool for characterizing the composition of soil organic matter and how it is altered by land use or the addition of organic amendments like biochar. It can help determine the stability and recalcitrance of carbon in different soil pools (Tatzber *et al.*, 2007).
- **Electron Microscopy:** High-resolution imaging with Scanning Electron Microscopy (SEM) and Transmission Electron Microscopy (TEM), often coupled with Energy Dispersive X-ray Spectroscopy (EDS) for elemental analysis, provides direct visual evidence of pedogenic processes at the micro-scale. Researchers can use SEM to visualize the weathering rinds on glass shards in a Technosol, the colonization of a microplastic particle by microbial biofilms, or the association of heavy metal particles with clay surfaces.

Isotopic and Geochemical Tracers: Unravelling Sources and Timescales

Isotopes provide powerful tools for tracing the source of materials and constraining the timing of pedogenic processes.

- **Fallout Radionuclides:** The atmospheric nuclear weapons testing in the 1950s and 1960s released several artificial radionuclides, most notably Cesium-137 (^{137}Cs) and Plutonium-239+240 ($^{239+240}Pu$). This created a global fallout peak around 1963, which serves as an unambiguous time marker in accumulating soil profiles and sediments. Once in the soil, ^{137}Cs is strongly adsorbed to clay particles. By comparing the inventory of ^{137}Cs in a soil profile to a stable reference site, scientists can accurately quantify the net soil loss or gain that has occurred over the past ~60 years, providing invaluable data on the rates of modern soil erosion (Walling & Quine, 1991).
- **Lead (Pb) and other Stable Metal Isotopes:** Lead has four stable isotopes, and the ratios between them (e.g., $^{206}Pb/^{207}Pb$) vary depending on the geological age and origin of the lead ore. This allows researchers to "fingerprint" different sources of lead pollution. For example, lead from Australian mines (used in gasoline in many parts of the world) has a very different isotopic signature from lead from North American ores or from natural background soil minerals. By analyzing the isotopic composition of lead in soil profiles, scientists can reconstruct the history of atmospheric lead deposition and apportion the contributions from different sources like gasoline, industry, and paint (Komárek *et al.*, 2008). Similar principles are now being applied to other metals like zinc, mercury, and copper.
- **Stable Isotopes of Light Elements (C, N, S):** The stable isotope ratios of carbon ($^{13}C/^{12}C$, expressed as $\delta^{13}C$) and nitrogen ($^{15}N/^{14}N$, expressed as $\delta^{15}N$) are powerful tracers of biogeochemical cycles. For instance, $\delta^{13}C$ can be used to track the replacement of native C3 vegetation (like forests) with C4 crops (like corn or sugarcane), providing a quantitative measure of the turnover of soil organic matter after land-use change. The $\delta^{15}N$ value of soils often increases with the application of synthetic fertilizers and animal manures, allowing it to be used as a tracer for agricultural pollution in watersheds.

Molecular Biology and 'Omics' Technologies: Decoding the Soil Microbiome

The soil microbiome is the unseen engine driving nearly all soil functions. Anthropogenic pressures cause profound shifts in these communities. The 'omics' revolution has provided a culture-independent window into this microbial world.

- **Metagenomics:** This is the study of the total genetic material recovered directly from a soil sample. High-throughput sequencing of this DNA allows researchers to answer the question: "Who is there?". It provides a comprehensive census of the microbial community, revealing its diversity, composition, and the genetic potential for various functions (e.g., genes for degrading a specific pollutant or for antibiotic resistance) (Fierer, 2017).
- **Metatranscriptomics and Metaproteomics:** These techniques go beyond the genetic potential to look at function. Metatranscriptomics sequences the messenger RNA (mRNA) to reveal which genes are actively being expressed ("what are they trying to do?"), while metaproteomics identifies the actual proteins being produced ("what are they actually doing?"). These functional 'omics' can provide direct evidence of how the microbial community is responding to a stressor, for example, by upregulating the production of enzymes to break down a hydrocarbon contaminant.

- **Metabolomics:** This is the large-scale study of small molecules, or metabolites, within the soil. These metabolites are the end products of microbial and plant metabolism and provide a direct snapshot of the biochemical activity in the soil. Analyzing the soil metabolome can reveal the intricate chemical communication happening between organisms and how this is disrupted by contaminants or other human impacts.
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Table 2: Comparison of Natural vs. Anthropogenic Pedogenesis

Attribute	Natural (Holocene) Pedogenesis	Anthropogenic Pedogenesis	Key References
Dominant Drivers	Climate, organisms, relief, parent material	Human activities (agriculture, urbanization, etc.) often overriding natural factors.	Richter & Yaalon (2012)
Timescale	10^3-10^6 years	10^0-10^2 years (human timescale)	Zalasiewicz *et al.* (2017)
Rates	Slow, incremental. Soil formation ~0.1 mm/yr.	Rapid, often catastrophic. Erosion >1 mm/yr; formation of Technosols can be instantaneous.	Montgomery (2007)
Parent Material	Geogenic (bedrock, glacial till, alluvium)	Anthropogenic (urban fill, mine spoils, waste) or heavily modified geogenic material.	Scalenghe & Marsan (2009)
Horizons	Genetically related, gradual/clear boundaries (A, E, B, C).	Often unrelated, sharp/discontinuous layers (Ap, fill layers, technic hardpans), or absent.	IUSS Working Group WRB (2015)
Stratigraphy	Follows geological principles (e.g., superposition).	Often inverted or chaotic due to excavation, filling, and mixing.	Ford *et al.* (2014)
Chemical Signatures	Controlled by natural weathering and biogeochemical cycles.	Dominated by anthropogenic inputs: legacy nutrients (P), contaminants (metals, organics), extreme pH.	Amundson *et al.* (2015)
Spatial Pattern	Correlated with landscape position, climate gradients.	Correlated with land-use history, infrastructure, property boundaries.	Lehmann & Stahr (2007)

Emerging Challenges in Anthropocene Pedogenesis

The novel materials and pressures of the Anthropocene are giving rise to a host of new and complex challenges for soil science and environmental management. This section focuses on the most significant of these: the genesis and management of Technosols, and the insidious, global proliferation of emerging contaminants.

Technosols: Classifying, Understanding, and Managing the Soils of Our Making

Technosols are the ultimate expression of anthropogenic pedogenesis. They are not simply "disturbed" soils; they are new entities formed in, on, or from materials that owe their existence to human activity. Their extent is growing with every new construction project, landfill, and mine.

The Challenge of Classification and Mapping

Classifying Technosols is inherently difficult due to their extreme heterogeneity and the absence of traditional genetic horizons. The World Reference Base for Soil Resources (IUSS Working Group WRB, 2015) has made a crucial step forward by formally recognizing this group. A soil qualifies as a Technosol if it contains a significant amount of technic hard material (e.g., concrete, asphalt) or has a high concentration of artefacts (human-made objects like plastic, glass, brick fragments). The system then uses a series of qualifiers to describe the nature of the material, such as Urbic (containing urban fill), Spolic (mine spoil), Garbic (landfill waste), or Hydric (dredge spoils). Despite this framework, mapping Technosols remains a formidable challenge. Their properties can vary dramatically over meters or even centimeters, a level of complexity that defies traditional soil survey methods. High-resolution proximal sensing, combined with historical land-use records and geotechnical data, is proving essential for characterizing these "Frankenstein" soils.

Novel Biogeochemical Processes and Ecological Trajectories

The biogeochemical processes in Technosols are fundamentally different from those in natural soils. The weathering of artificial parent materials releases a unique suite of elements and creates novel chemical conditions. The slow dissolution of silicate glass or the carbonation of concrete are pedogenic processes unique to the Anthropocene. Microbial colonization of these substrates is a key area of research. How do microbial communities adapt to high pH, high salinity, and the presence of contaminants? Can they extract nutrients from unconventional materials? There is evidence that some microbes can colonize and even derive energy from materials like asphalt (Tarr *et al.*, 2020). The ecological succession on these soils is also unique. Often, the first colonizers are non-native, stress-tolerant plant species. Understanding these novel ecological trajectories is crucial for predicting the long-term development of these landscapes.

Management for Ecosystem Services

Despite their often-degraded state, Technosols are the soils upon which a growing majority of the human population lives. Managing them to provide essential ecosystem services is a critical urban challenge. There is growing interest in "technosol engineering" or the creation of "designer soils." This involves the intentional blending of various waste streams (e.g., construction debris, compost, biochar, dredge spoils) to create a substrate with specific physical and chemical properties tailored for a particular purpose, such as green roof media, stormwater bioretention cells, or substrates for urban agriculture (Morel *et al.*, 2015). However, the primary management challenge remains the mitigation of risks from legacy contamination. This often involves strategies like "capping," where a clean layer of soil is placed over the contaminated material to break exposure pathways, or phytoremediation, where specific plants are used to extract, stabilize, or degrade contaminants in the soil.

Emerging Contaminants: The Invisible, Persistent Threat

Beyond the "classic" legacy contaminants, Anthropocene soils are becoming the final sink for a new and insidious generation of pollutants whose environmental fate and long-term effects are only beginning to be understood.

Microplastics: A Ubiquitous and Persistent Pollutant

Microplastics (MPs), plastic particles < 5 mm in size, are now found in soils from the most remote mountain peaks to the most intensively farmed fields. The primary sources to terrestrial systems are the application of sewage sludge (which concentrates MPs from wastewater), the breakdown of plastic mulch films used in agriculture, tire wear particles, and atmospheric deposition (Horton *et al.*, 2017). Once in the soil, their persistence is measured in centuries or millennia. The impacts of MPs are multifaceted:

- **Physical Effects:** MPs can alter soil bulk density, water holding capacity, and aggregation. Their shape is important; fibers, for example, can create channels that increase water infiltration but also the leaching of nutrients, while films can create impermeable layers (de Souza Machado *et al.*, 2018).
- **Chemical Effects:** Plastics are not inert. They contain a cocktail of chemical additives plasticizers like phthalates, flame retardants like PBDEs, and stabilizers like bisphenol A (BPA) that can leach into the soil over time. Many of these are known endocrine disruptors. Furthermore, the surface of MPs can adsorb other pollutants from the soil, like heavy metals or pesticides, acting as a "vector" that can alter their transport and bioavailability (Rillig *et al.*, 2021).
- **Biological Effects:** Soil organisms, from earthworms to collembola, can ingest MPs. This can cause physical damage to their digestive systems, inflammation, and reduced growth and reproduction. There is also growing evidence that MPs can alter the composition and function of the soil microbiome and disrupt the crucial symbiotic relationship between plants and mycorrhizal fungi.

Pharmaceuticals and Personal Care Products (PPCPs): A Chronic Low-Dose Exposure

Our global consumption of pharmaceuticals for human and veterinary medicine has led to their continuous release into the environment. As many of these compounds are not fully removed by wastewater treatment, they concentrate in sewage sludge (biosolids). The application of biosolids to agricultural land as a fertilizer is a major pathway for PPCPs entering the soil environment. Antibiotics, antidepressants, hormones, beta-blockers, and anti-inflammatory drugs are now routinely detected in agricultural soils (Boxall, 2012). The most significant concern is the presence of antibiotics, which can exert a selective pressure on the soil microbiome, promoting the proliferation of antibiotic-resistant bacteria and the spread of antibiotic resistance genes (ARGs). This "environmental reservoir" of ARGs is a major threat to public health, as these genes can potentially be transferred to human pathogens (Zhu *et al.*, 2013). Other PPCPs can be taken up by crops, leading to human exposure through the food chain, though the long-term health consequences of this chronic, low-dose exposure are still largely unknown.

Engineered Nanomaterials (ENMs): A Novel Class of Contaminant

ENMs are materials with at least one dimension between 1 and 100 nm. Their novel quantum-scale properties have led to their incorporation into thousands of consumer products. Silver nanoparticles (AgNPs) are used for their antimicrobial properties in textiles and medical devices; titanium dioxide (TiO_2) and zinc oxide (ZnO) nanoparticles are used in sunscreens and paints. The disposal of these products leads to the accumulation of ENMs in soils via biosolids and other waste streams. Their small size and high surface-area-to-volume ratio make them highly reactive. AgNPs, for example, have been shown to be toxic to a wide range of beneficial soil microorganisms, potentially disrupting key nutrient cycles like nitrification (Judy *et al*., 2011). The long-term fate and behavior of ENMs in the complex soil environment whether they dissolve, aggregate, or are transported is a critical area of ongoing research.

Per- and Polyfluoroalkyl Substances (PFAS): The "Forever Chemicals"

PFAS are a large class of synthetic chemicals characterized by a chain of carbon atoms bonded to fluorine atoms. The carbon-fluorine bond is one of the strongest in organic chemistry, making these compounds extremely resistant to degradation. This persistence has earned them the name "forever chemicals." They have been used for decades in a vast range of industrial and consumer products, including non-stick coatings (Teflon), stain-resistant fabrics, and, most notably, aqueous film-forming foams (AFFF) used to fight fuel fires. Widespread contamination of soils and groundwater has occurred at military bases, airports, and industrial sites where these foams were used (Kucharzyk *et al*., 2017). PFAS are highly mobile in soil and can readily leach into groundwater and be taken up by plants, providing a direct pathway into the food chain. They are linked to a range of adverse health effects in humans, and their extreme persistence means that they represent a permanent contamination legacy and one of the most daunting remediation challenges of the 21st century.

Table 3: Advanced Analytical Techniques for Anthropocene Soils

Technique Category	Specific Method	Principle	What It Measures/Reveals	References
Proximal Sensing	Vis-NIR Spectroscopy	Measures reflectance of light (350-2500 nm); absorption features relate to molecular bonds.	Soil organic carbon, clay content, moisture, some minerals. High-resolution spatial mapping.	Viscarra Rossel *et al*. (2011)
	Portable XRF (pXRF)	X-ray source excites atoms, which fluoresce at element-characteristic energies.	Total elemental composition, especially heavy metals (Pb, As, Zn, Cu). Rapid site screening.	Weindorf *et al*. (2014)
Microscopy /Spectroscopy	Synchrotron-XAS	Measures absorption of high-energy X-rays to probe the electronic structure of a target element.	Chemical speciation (oxidation state, bonding environment) of contaminants and nutrients.	Manceau *et al*. (2002)
	SEM-EDS	Scans a surface with a focused electron beam; detects secondary electrons for imaging and X-rays for elemental analysis.	Micro-morphology, particle shape, elemental composition of individual soil components.	
Isotopic Tracers	Fallout Radionuclides (^{137}Cs)	Measures the inventory of ^{137}Cs from nuclear testing fallout relative to a stable reference site.	Quantitative rates of soil erosion or deposition over the last ~60 years.	Walling & Quine (1991)
	Stable Lead Isotopes ($^{206}Pb/^{207}Pb$)	Measures the ratio of lead isotopes, which varies by the geological origin of the lead ore.	Source apportionment of lead pollution (e.g., gasoline vs. industrial vs. natural).	Komárek *et al*. (2008)
'Omics' Technologies	Metagenomics	High-throughput sequencing of total DNA extracted from soil.	Microbial community composition (who is there?) and genetic potential (e.g., for degradation, resistance).	Fierer (2017)
	Metaproteomics	Mass spectrometry analysis of all proteins extracted from a soil sample.	The actual proteins being expressed by the microbiome, revealing active functional pathways.	

Table 4: Major Classes of Contaminants in Anthropocene Soils

Contaminant Class	Common Examples	Primary Anthropogenic Sources	Key Soil-Related Concerns	References
Heavy Metals & Metalloids	Lead (Pb), Cadmium (Cd), Mercury (Hg), Arsenic (As)	Leaded gasoline (legacy), industrial emissions, mining, pesticides, paints.	High toxicity, persistence, potential for food chain transfer, human health risks (neurotoxicity, carcinogenicity).	Mielke & Reagan (1998)
Persistent Organic Pollutants (POPs)	PAHs, PCBs, Dioxins	Incomplete combustion of fossil fuels, industrial byproducts, legacy electrical equipment.	High persistence, bioaccumulation in food webs, toxicity (carcinogenic, endocrine disruption).	Lohmann *et al.* (2007)
Microplastics	Polyethylene (PE), Polypropylene (PP), PET, PVC	Sewage sludge application, plastic mulch, tire wear, atmospheric deposition.	Extreme persistence, alteration of soil physical properties, vector for other pollutants, ingestion by soil fauna.	Rillig *et al.* (2021)
PPCPs	Antibiotics (e.g., tetracycline), Hormones, Antidepressants	Biosolids from wastewater treatment, application of animal manure.	Promotion of antibiotic resistance, potential uptake by crops, unknown long-term ecological effects.	Boxall (2012)
PFAS	PFOA, PFOS	Firefighting foams (AFFF), industrial manufacturing, consumer products (e.g., non-stick coatings).	Extreme persistence ("forever chemicals"), high mobility in soil and water, bioaccumulation, human health risks.	Kucharzyk *et al.* (2017)
Engineered Nanomaterials	AgNPs, TiO_2 NPs, ZnO NPs	Consumer products (sunscreens, textiles), industrial applications; disposal via wastewater.	Novel toxicological properties, potential toxicity to soil microbes, uncertain long-term fate and transport.	Judy *et al.* (2011)

Table 5: Management and Remediation Strategies for Anthropocene Soils

Strategy	Description	Applicability	Limitations	References
Physical Containment (Capping)	Placing a clean barrier (e.g., soil, geotextile, concrete) over contaminated soil to break exposure pathways.	Widespread use in urban and industrial site redevelopment (brownfields).	Does not destroy contaminants; requires long-term maintenance and monitoring of cap integrity.	
Ex-situ Remediation (Soil Washing)	Excavating soil and treating it with a liquid solution to wash out contaminants. The "clean" soil is returned to the site.	Sites with high levels of leachable contaminants (metals, some organics).	High cost, generates a concentrated waste stream, destroys soil structure and biology.	
In-situ Chemical Stabilization	Adding amendments (e.g., phosphate minerals, iron oxides, biochar) to the soil to bind contaminants, reducing their mobility and bioavailability.	Large sites with metal and metalloid contamination where excavation is not feasible.	Contaminants remain in place; long-term stability of the bound forms can be uncertain.	
Bioremediation	Using microorganisms (bioaugmentation or biostimulation) to degrade organic contaminants into less harmful substances.	Soils contaminated with petroleum hydrocarbons and some other biodegradable organics.	Can be slow; effectiveness depends on contaminant type and environmental conditions.	
Phytoremediation	Using specific plants to extract (phytoextraction), stabilize (phytostabilization), or degrade (phytodegradation) contaminants.	Large, low-to-moderately contaminated sites. Good for metals and some organics.	Slow process; limited by root depth; potential for contaminants to enter food web via herbivores.	
Technosol Engineering	Intentionally blending waste materials (e.g., construction debris, compost, ash) to create a "designer soil" for a specific function.	Urban greening projects (green roofs, parks), land reclamation, creating substrates for specific functions.	Requires deep understanding of material properties; potential for unintended leaching of contaminants from waste materials.	Morel *et al.* (2015)

Conclusion and Future Directions

The evidence is overwhelming and unequivocal: humanity has become the single most powerful pedogenic factor on Earth. The Anthropocene is not a distant future concept; its signature is deeply and often irrevocably inscribed in the soil beneath our feet in the homogenized plough layers of our farmlands, the chaotic stratigraphy of our cities, the toxic legacy of our industries, and the invisible but pervasive chemical cocktail of emerging contaminants that now blankets the globe. The classical models of soil formation, while still providing a crucial foundation, are no longer sufficient to describe or predict the evolution of these novel, human-dominated systems. Soils can no longer be viewed as purely natural bodies but must be understood as complex, hybrid systems forged at the dynamic interface of geological history and human endeavor.

This review has systematically charted the multifaceted ways in which human activities are redirecting pedogenesis, from the brute force of the plough and bulldozer to the insidious, molecular-scale interventions of synthetic chemistry. We have also surveyed the powerful modern analytical toolbox that is allowing scientists to decipher these complex new systems with unprecedented clarity. Yet, despite these advances, our understanding remains nascent, and the challenges ahead are monumental. The future of soil science in the Anthropocene must be integrative, interdisciplinary, proactive, and squarely focused on developing sustainable solutions for a planet under pressure.

From this synthesis, several critical research directions emerge as paramount for the coming decades:

1. **Developing a Predictive, Quantitative Framework for Anthropocene Pedogenesis:** We must move beyond descriptive studies and build robust, process-based models that can forecast the evolution of soils under various scenarios of land use, climate change, and technological development. This will require the integration of high-resolution spatial data, long-term monitoring, and mechanistic understanding of novel weathering and biogeochemical processes to predict critical changes in soil health, function, and the ecosystem services they provide.
2. **Elucidating the "Total" Impact of the Chemical Universe:** The long-term ecological consequences of the complex mixture of emerging contaminants the "chemical cocktail" effect is a terrifying knowledge gap. We need long-term, field-based research to understand the interactions, synergistic effects, and ultimate fate of microplastics, PPCPs, ENMs, and PFAS in real-world soil systems. What are the evolutionary pressures they exert on the soil microbiome? What are the tipping points beyond which soil functions irreversibly decline?
3. **Harnessing the Potential of Technosols and the Circular Economy:** Instead of viewing Technosols and other waste materials solely as problems, we must aggressively research their potential as resources. The development of safe, effective, and predictable methods for "technosol engineering" is critical for urban sustainability, land reclamation, and climate adaptation (e.g., creating "sponge city" soils for stormwater management). This is the essence of applying soil science to the circular economy: closing waste loops by creating valuable, functional soil systems.
4. **Deepening our Understanding of the Soil Microbiome as a Sentinel and Engine of Change:** The soil microbiome is both a sensitive indicator of anthropogenic stress and a potential engine for remediation and resilience. Future research must leverage the full power of 'omics' technologies to understand how to manage these microbial communities to enhance soil health, suppress pathogens and antibiotic resistance, and degrade recalcitrant pollutants.
5. **Integrating Soil Science into Policy and Global Governance:** Soil health is fundamental to achieving nearly all of the UN Sustainable Development Goals, from ending hunger (SDG 2) to ensuring clean water (SDG 6) and combating climate change (SDG 13). Soil scientists have a critical responsibility to more effectively translate their knowledge into actionable policies for sustainable soil management at local, national, and international levels. The Anthropocene demands that soil be given the same level of policy attention as air and water.

In conclusion, the study of pedogenesis in the Anthropocene is not just a sub-discipline of soil science; it is a central challenge for all of environmental science. The health, resilience, and security of our soils are inextricably linked to the future health, resilience, and security of human civilization. By embracing new tools, asking new and daring questions, and working across disciplines, soil scientists can provide the essential knowledge needed to navigate the complexities of this new human-dominated epoch and, ultimately, to learn how to build a more sustainable and enduring future on the very foundation we are so rapidly transforming.

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