



## Conventional Fuels: Understanding Environmental Impacts and Advancing Degradation Strategies for Sustainability

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Conventional fuels are naturally occurring fossil fuels that have formed over millions of years through the anaerobic decomposition of organic matter. These fuels are primarily categorised as coal, petroleum (crude oil) and its derivatives such as diesel and petrol and natural gas, which consists mainly of methane. They are essential for modern society, supporting electricity generation, transportation, industrial processes and overall economic development. Their extensive use has enabled rapid technological advancement and improved living standards worldwide. However, the continued dependence on conventional fuels has raised serious environmental concerns, including greenhouse gas emissions, air and water pollution and land degradation. These challenges highlight the urgent need to balance energy demands with environmental protection and sustainable development. Understanding the formation, environmental impacts and effective degradation strategies of conventional fuels is therefore essential for developing sustainable solutions and guiding future energy transitions.

### Geological Formation and Composition of Conventional Fuels

Coal is formed from the decomposition of plant material in swampy environments, which subsequently undergoes compaction and metamorphism under conditions of high pressure and temperature. It is rich in carbon (60–95%) and contains other elements such as hydrogen, sulphur, nitrogen and oxygen. The energy density of coal typically ranges from 18 to 30 MJ/kg, depending on its grade, such as anthracite, bituminous or lignite. Petroleum originates from the remains of marine microorganisms that were buried under sediment millions of years ago. Over geological time, heat and pressure transformed this organic matter into a complex mixture of liquid and gaseous hydrocarbons, including paraffins, cycloalkanes and aromatics. Petroleum possesses a high energy density of approximately 42 to 47 MJ/kg and is vital for the petrochemical industry and the production of lubricants and asphalt. Natural gas forms from buried organic matter (plankton and plants) in oxygen-free conditions, undergoing thermal breakdown known as catagenesis deep underground. It is primarily composed of methane (70–90%), with smaller amounts of ethane, propane, butane and CO<sub>2</sub>. Natural gas has the highest energy density among the three, ranging from 50 to 55 MJ/kg and is widely used for domestic fuel and fertilizer production.

### Environmental Impact of Conventional Fuels

The environmental consequences of using conventional fuels are vast and affect the atmosphere, land and water systems.

#### Atmospheric Pollution and Global Climate Change

The combustion of fossil fuels is a major source of greenhouse gases (GHGs) and air pollutants. Carbon dioxide (CO<sub>2</sub>) is the primary contributor to global warming, while

methane (CH<sub>4</sub>) is a potent GHG with an even higher global warming potential. Nitrogen oxides (NO<sub>x</sub>) contribute to smog formation and ozone depletion and sulphur dioxide (SO<sub>2</sub>) from sulphur-containing fuels leads to acid rain and respiratory illnesses. Incomplete combustion releases particulate matter (PM<sub>2.5</sub> and PM<sub>10</sub>) and carbon monoxide (CO), which can cause severe cardiovascular diseases and reduce oxygen transport in the bloodstream. Furthermore, fuel evaporation releases volatile organic compounds (VOCs) that react with NO<sub>x</sub> to form ground-level ozone. These emissions trap outgoing infrared radiation, causing a rise in global average temperatures. This warming accelerates ice melt, leading to sea-level rise and threatening coastal ecosystems. Additionally, the absorption of CO<sub>2</sub> by oceans causes acidification, which harms coral reefs and marine life.

### **Land Degradation and Soil Contamination**

Coal mining and oil exploration activities often remove topsoil, disturb soil structures and reduce overall fertility. Accidental spillages and leakages introduce toxic hydrocarbons into the soil, which inhibit microbial activity and plant growth. The extraction and combustion processes also release heavy metals like lead, mercury, arsenic and cadmium, which accumulate in the soil and disrupt beneficial fauna like earthworms that are essential for nutrient cycling. Oil residues can clog soil pores, decreasing water infiltration and aeration. Furthermore, the disposal of coal ash contaminates agricultural land with toxic elements, making it unsuitable for restoration.

### **Water Pollution**

Water bodies are frequently contaminated by accidental oil spills during drilling and transportation, which causes severe harm to aquatic ecosystems. Refinery effluents introduce toxic hydrocarbons that reduce oxygen availability in the water. Coal mining contributes to acid mine drainage, where the oxidation of sulphide minerals produces acidic water that lowers pH and mobilizes toxic metals into groundwater. Thermal pollution is another concern, as power plants discharge heated water into rivers, reducing dissolved oxygen levels. Persistent pollutants from fuels can accumulate in aquatic organisms and bio magnify through the food chain, posing significant risks to human health.

## **Strategies for the Degradation of Conventional Fuel Pollutants**

Scientific innovation has provided several pathways to degrade these persistent pollutants and mitigate their impact.

### **Biodegradation and Phytoremediation**

Biodegradation involves using microorganisms like *Pseudomonas*, *Bacillus*, *Alcanivorax* and *Rhodococcus* to utilize petroleum hydrocarbons as a carbon source. These microbes produce enzymes such as oxygenases and dehydrogenases that convert complex hydrocarbons into simpler, less toxic compounds. Fungi, including *Aspergillus* and *Penicillium*, are also effective at degrading high molecular weight hydrocarbons. The process can be accelerated through bio-stimulation, which involves adding nutrients like nitrogen and phosphorus and increasing oxygen levels. Phytoremediation is a plant-based technique used to remove or stabilize fuel-derived pollutants in soil and water. Several plants have been identified for this purpose, including *Helianthus annuus* (sunflower), *Brassica juncea* (mustard), *Medicago sativa* (alfalfa), *Cynodon dactylon* (Bermuda grass), etc.

### **Photocatalytic and Chemical Degradation**

Photocatalytic degradation is an advanced oxidation process that uses light-activated semiconductor catalysts like titanium dioxide (TiO<sub>2</sub>), zinc oxide (ZnO) and iron oxide (Fe<sub>2</sub>O<sub>3</sub>). Under UV or visible light, these catalysts generate reactive oxygen species, such as hydroxyl and superoxide radicals, which oxidize hydrocarbons into CO<sub>2</sub>, water and inorganic ions. Chemical degradation utilizes oxidants like ozone (O<sub>3</sub>), hydrogen peroxide (H<sub>2</sub>O<sub>2</sub>), etc., to attack hydrocarbon molecules rapidly. This method is often used as a pre-treatment to break down long-chain aliphatic and aromatic hydrocarbons into smaller, more biodegradable intermediates for subsequent microbial action.

### Carbon Capture, Utilization and Storage (CCUS)

Carbon Capture, Utilization and Storage (CCUS) is an important technological approach aimed at reducing carbon dioxide emissions from major industrial and energy sources. It involves capturing CO<sub>2</sub> from power plants and industrial processes using pre-combustion, post-combustion or oxy-fuel technologies, followed by its compression and transport. The captured CO<sub>2</sub> can then be utilized in the production of value-added products such as synthetic fuels, chemicals, urea and construction materials, or permanently stored in deep geological formations like depleted oil and gas reservoirs and saline aquifers. By preventing large volumes of CO<sub>2</sub> from entering the atmosphere, CCUS plays a crucial role in mitigating climate change, particularly in sectors where complete decarbonization is challenging.

### Policy Interventions

Effective management of conventional fuel impacts requires robust policy frameworks. Strict emission norms, such as BS-VI and Euro standards, help reduce air pollutants from vehicles. Carbon pricing mechanisms, including carbon taxes and emission trading systems, discourage excessive fossil fuel use. Mandatory Environmental Impact Assessments (EIAs) regulate industrial activities to minimize damage, while international agreements like the Paris Agreement aim to limit global emissions. Furthermore, government incentives for renewable energy accelerate the transition away from conventional fuels.

### Conclusion

Conventional fuels remain essential for energy and economic development, but their environmental impacts, such as climate change, pollution and ecosystem degradation, are significant and unsustainable. Scientific approaches such as biodegradation and phytoremediation offer promising and sustainable solutions for managing pollutants, while technologies like CCUS provide a pathway to reduce the carbon footprint of existing industries. Achieving long-term environmental sustainability will require an integrated approach that combines these scientific innovations with strong policy support and a gradual transition toward renewable energy sources.

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