General Overview of Environmental Epidemiology

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The derivation of "epidemiology"

The word "epidemiology" is from the Greek words:

- epi—prefix meaning 'on' or 'upon'
- demos—root meaning 'the people'
- logos—suffix meaning 'the study'

Epidemiology is, therefore, the study of what is upon the people.

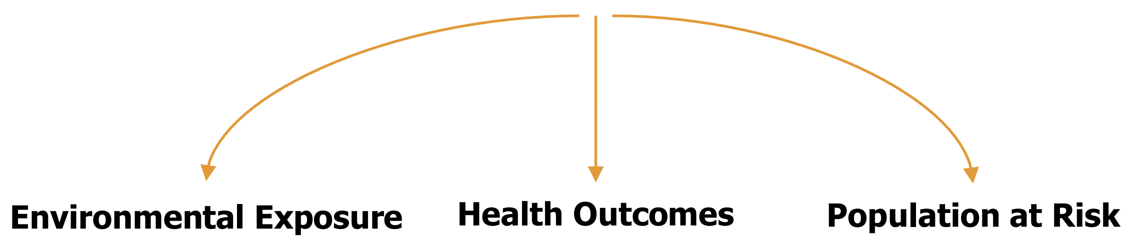
What is Environmental Epidemiology?

- Environmental epidemiology investigates the relationship between environmental exposures and health outcomes in populations.

- It tries to answer questions like:
- Does exposure to air pollution increase cardiovascular disease?
- Do pesticides increase cancer risk?
- How does climate change affect infectious diseases?
- It combines methods from **epidemiology, environmental science, toxicology, statistics, and public health**.

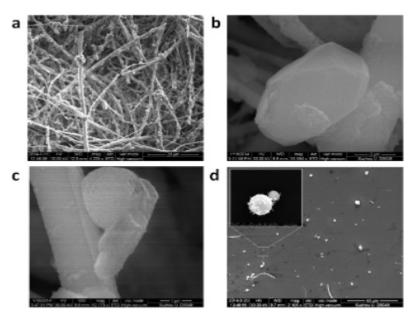
Major Components of Environmental Epidemiology

Environmental epidemiology mainly deals with three components:



Environmental Exposure

- These are external factors people are exposed to.
- Examples:
  - Air pollutants (PM2.5, NO_2, SO_2)
  - Water contaminants (arsenic, fluoride)
  - Heavy metals (lead, mercury)
  - Radiation
  - Noise pollution
  - Temperature and climate factors
  - Chemicals (pesticides, industrial chemicals)



- Example: Exposure to Particulate Matter (PM2.5) has been linked to cardiovascular and respiratory diseases.

Particulate Matter (PM2.5)

Particulate Matter (PM2.5) refers to airborne particles or liquid droplets with diameters of 2.5 micrometers or smaller—roughly 1/30th the width of a human hair. These fine articles are a key air pollutant linked to both environmental and health impacts, and they serve as a major indicator of air quality worldwide.

Key facts

- **Size threshold:** ≤2.5 µm in diameter
- **Primary sources:** Combustion, industry, vehicle exhaust, chemical reactions
- **WHO annual guideline:** 5 µg/m³ (updated 2021)
- **Typical monitoring metric:** Annual mean concentration (µg/m³)
- **Main health risks:** Respiratory and cardiovascular diseases

Composition and sources

PM2.5 includes a complex mixture of organic chemicals, metals, sulfates, nitrates, and carbon compounds such as black

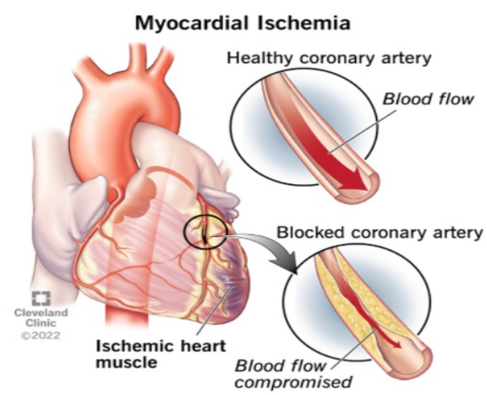
and organic carbon. These particles areemitted directly from combustion processes such as motor vehicles, power plants,and wood burningor form secondarily when gases like sulfur dioxide and nitrogenoxides react in the atmosphere. Natural sources in clude dust, wildfires, and volcanic activity.

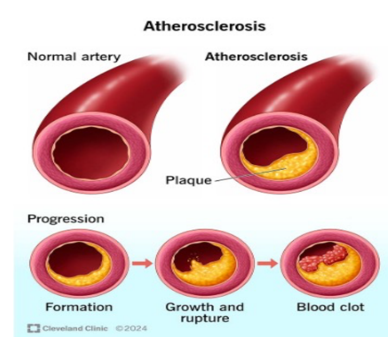
Health and environmental impact

Because of their small size, PM2.5 particles penetrate deeply into the lungs and canenter the bloodstream, increasing the risk of asthma, br onchitis, lung cancer, heart attack, and premature death. Short-term exposure irritates the eyes, throat, and respiratory tract, while longterm exposure contributes to chronic disease andmortality. Environmentally, PM2.5 reduces visibility(haze) and influences climate by scattering and absorbing sunlight.

Health Outcomes

- Environmental exposures can lead to various diseases.
- Examples:
- Respiratory diseases (asthma, COPD)
- Cardiovascular disease
- Cancer
- Birth defects
- Neurological disorders
- Infectious diseases





- Mental health disorders
- For example, long-term exposure to air pollution increases risk of Ischemic Heart Disease and Stroke.

Ischemic heart disease

Ischemic heart disease (IHD), also known as coronary artery or coronary heart disease, is a condition in which reduced or blocked blood flow in the heart's arteries deprives the heart muscle of oxygen. It is the world's leading cause of death and a major source of disability, affecting both men and women globally.

Key facts

- **Primary cause:** Atherosclerosis (plaque buildup in coronary arteries).
- **Common forms:** Stable angina, unstable angina, myocardial infarction.
  Major risk factors: Smoking, hypertension, diabetes, high cholesterol, obesity, inactivity.
- **Leading consequence:** Heart attack, heart failure, or sudden cardiac death.
- **Global impact (2024):** Leading single cause of mortality worldwide.

Stroke

A stroke is a **medical emergency** in which blood flow to a part of the brain is interrupted or reduced, causing brain cells to die within minutes. It is a leading global cause of longterm disability and death, and rapid treatment greatly improves survival and recovery outcomes.

Key facts

- **Types:** Ischemic (≈85%), hemorrhagic (≈15%).
- **Core mechanism:** Loss of brain oxygen and nutrients due to blocked or ruptured vessel.
- **Primary risk factors:** Hypertension, smoking, diabetes, high cholesterol, atrial fibrillation.
- **Primary symptoms:** Sudden weakness, facial droop, speech difficulty.
- **Treatment window:** Minutes to hours depending on stroke type.

Population at Risk

- Environmental epidemiology studies **populations rather than individuals**.
- Examples:
  - Urban vs rural populations
  - Occupational groups
  - Children and elderly
  - Low socioeconomic groups
- Certain groups are more vulnerable, such as children, pregnant women, and people with pre-existing diseases.

Types of Environmental Exposures

1. Physical Exposures

Examples:

- Radiation
- Noise
- Temperature
- UV radiation

Example disease: Skin cancer caused by UV radiation.

2. Chemical Exposures

Examples:

- Heavy metals
- Industrial chemicals
- Pesticides
- Air pollutants

Example:
Exposure to arsenic in groundwater causes:

- Skin lesions
- Cancer
- Cardiovascular disease

3. Biological Exposures

Examples:

- Bacteria
- Viruses
- Parasites
- Allergens

Example:
Climate conditions influence the spread of diseases such as Malaria.

Major Environmental Risk Factors

According to the World Health Organization, key environmental risk factors include:

Air Pollution

- Outdoor pollution
- Indoor pollution from biomass fuel
- Tobacco smoke

Air pollution is strongly linked to:

- Chronic Obstructive Pulmonary Disease (COPD)
- Lung Cancer

Water Pollution

Contaminated water causes:

- Diarrheal diseases
- Cholera
- Typhoid

Example disease: Cholera

Soil Pollution

Examples:

- Pesticides
- Heavy metals

This can affect:

- Food safety
- Agriculture
- Human health

Climate Change

Climate change influences:

- Heat waves
- Vector-borne diseases
- Food security

Example disease: Dengue Fever

Study Designs in Environmental Epidemiology

1. Ecological Study

An ecological study examines the relationship between exposure and disease at the population or group level, rather than individual level.

Example

Comparing:

- Average air pollution levels in cities
- Mortality rates in those cities

Example research question:

Does higher exposure to Particulate Matter (PM2.5) across cities increase cardiovascular mortality?

Data Structure

Group-level data such as:

- Country
- City
- District
- Time period

Example dataset

City	Average PM2.5	Mortality Rate
City A	35	120
City B	15	80

Advantages

- Easy and inexpensive
- Useful for hypothesis generation

- Good for global comparisons

Example: *Studies from the Global Burden of Disease Study.*

Limitations

- **Ecological fallacy** (group association may not apply to individuals)
- Cannot control confounding well.

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2. Cross-Sectional Study

A cross-sectional study measures exposure and outcome at the same time.

Example

Measure:

- PM2.5 exposure
- Blood pressure
- Cholesterol levels
- in participants at the same survey time.

Example research question:

Does long-term air pollution exposure increase prevalence of hypertension?

Data Collection

Data collected at a single point in time.

Example dataset

Person	PM2.5	Hypertension
1	30	Yes
2	18	No

Advantages

- Quick and inexpensive
- Good for estimating **disease prevalence**

Limitations

- Cannot establish **temporal relationship**
- Cannot infer causality

3. Case-Control Study

A case-control study compares people with a disease (cases) to people without the disease (controls) and looks back at their past exposures.

Example

Study whether pesticide exposure increases risk of Parkinson's Disease.

Cases: People with Parkinson's disease | ***Controls:*** People without the disease

Then assess their past exposure to pesticides.

Measure of Association

The association is measured using Odds Ratio (OR).

Example dataset

Group	Disease	Exposure
Cases	Yes	Past exposure
Controls	No	Past exposure

Advantages

- Efficient for rare diseases
- Requires smaller sample size
- Faster than cohort studies

Limitations

- Recall bias
- Selection bias
- Cannot measure incidence directly

4. Cohort Study

A cohort study follows individuals over time to see whether exposure leads to disease.

Example

Follow individuals exposed to high levels of Particulate Matter (PM2.5) to see if they develop cardiovascular disease.

Example outcomes:

- Stroke

- Ischemic Heart Disease

Measure of Association

Relative Risk (RR), Hazard Ratio (HR)

Types of Cohort Studies

A. **Prospective Cohort:** Exposure measured before disease occurs.

Example: Recruit participants → follow for 10 years

B. **Retrospective Cohort:** Both exposure and outcome occurred in the past, but records are used.

Example: Occupational exposure studies.

Example dataset

Exposure	Follow-up	Disease
Exposed	Time	Outcome
Unexposed	Time	Outcome

Advantages

- Strong evidence for causal inference
- Can measure incidence
- Can study multiple outcomes

Limitations

- Expensive
- Time-consuming
- Loss to follow-up

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5. Time-Series Study

Time-series studies are widely used in air pollution epidemiology. They examine short-term exposure effects using daily data.

Example

Researchers examine whether daily increases in pollution lead to increases in health events.

Outcomes:

- Mortality
- Hospital admissions

- Emergency visits

Statistical Models

Often use:

- Poisson regression
- Generalized additive models (GAM)

Commonly implemented using R programming language.

Example dataset

Day	PM2.5	Hospital Admissions
Day 1	35	120
Day 2	28	100

Advantages

- Good for short-term effects
- Controls for time trends

Limitations

- Cannot study long-term exposure effects.

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6. Panel Study

Panel studies repeatedly measure the same individuals over time.

Example

Participants wear personal monitors and researchers measure:

- PM2.5 exposure
- Lung function
- Blood pressure

at multiple times.

Example research
Air pollution exposure and lung function changes in children.

Advantages

- Captures short-term physiological responses
- Reduces between-person variability

Limitations

- Small sample sizes
- Expensive monitoring

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7. Panel Study

In rare cases environmental epidemiology includes intervention studies.

Example

Installing clean cookstoves and evaluating health outcomes.

Example outcome

Reduction in Chronic Obstructive Pulmonary Disease.

Types

- Randomized Controlled Trials
- Natural experiments

Example
Air pollution reductions after policy changes.

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8. Natural Experiments

These occur when environmental changes happen due to policy or external events.

Example

Closure of a coal power plant.

Researchers compare health outcomes:

- Before closure
- After closure

Such studies provide strong evidence for causality.

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9. Case-Crossover Study

Often used in air pollution and weather studies.

In this design: Each subject serves as their own control.

Example: If someone had a heart attack on a specific day:

Compare pollution levels:

- On the event day
- On control days

Outcome example: Myocardial Infarction.

Advantages

- Controls for personal confounders
- Useful for short-term exposure effects

Exposure Assessment

Exposure assessment is a critical part of environmental epidemiology.

Methods include:

Environmental Monitoring

Measurement of pollutants in:

- Air
- Water
- Soil

Example: PM2.5 monitoring stations.

Personal Exposure Monitoring

Devices worn by participants to measure exposure.

Example:

- Personal PM2.5 monitors.

Biomarkers

Chemical indicators measured in biological samples.

Examples:

- Blood led level
- Urinary arsenic

Modelling

Statistical models predict exposure levels.

Examples:

- Land Use Regression (LUR)
- Satellite-based exposure models

Exposure assessment is very difficult because:

- Critical exposures may have happened years or decades ago.
- Exposures may be very small (e.g., ppm or ppb).
- Exposures may be from multiple sources (e.g., different stove types) and by multiple routes (e.g., oral, dermal, inhalation).

- People cannot tell you what their exposures were.

Exposure Modeling in Environmental Epidemiology

Accurate exposure assessment is the **biggest challenge** in environmental epidemiology. People move between locations and monitoring stations are sparse, so researchers use **exposure models**.

1. Land Use Regression (LUR)

Predicts pollution levels using land-use variables.

Variables used:

- Road density
- Traffic intensity
- Industrial areas
- Population density
- Elevation

Model structure: $PM_{2.5} = \beta_0 + \beta_1(Traffic) + \beta_2(Population) + \beta_3(Industry) + \epsilon$

Advantages:

- High spatial resolution
- Good for urban exposure estimation

Limitations:

- Requires monitoring data

2. Satellite-based Exposure Models

Satellite data measure **aerosol optical depth (AOD)** which correlates with particulate matter.

Example satellite:

- NASA Terra Satellite

Researchers combine:

- Satellite AOD
- Ground monitoring
- Meteorology
- Chemical transport models

These models produce **1 km × 1 km $PM_{2.5}$ grids globally**.

Used by:

- Institute for Health Metrics and Evaluation in the Global Burden of Disease Study.

Advantages:

- Large spatial coverage
- Works in regions with no monitors

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3. Chemical Transport Models

These simulate **physical and chemical processes of air pollution**.
Examples:

- GEOS-Chem
- CMAQ

They simulate:

- Emissions
- Atmospheric chemistry
- Wind transport
- Deposition

Used to estimate:

- Source contributions
- Regional transport of pollution.

Statistical Methods Used

Environmental epidemiology heavily uses advanced statistics.
Examples:

- Generalized Linear Models (GLM)
- Generalized Additive Models (GAM)
- Mixed models
- Time-series models
- Distributed lag models
- Spatial analysis

For example, **air pollution studies often use** R programming language packages like mgcv to fit **GAM models**.

Measures of disease occurrence- Prevalence

The proportion of a population with a specific type of disease, as recorded at one point in time. *e.g., the proportion of children in a school who are diagnosed asthmatics*

$$Prevalence = \frac{Existing\ cases}{Total\ Population}$$

Prevalence could be two types:

Point Prevalence —Disease at a **specific time point**. (e.g., prevalence of Hypertension on January 1.)

Period Prevalence —Disease cases **during a time period**.(e.g., asthma prevalence during 2024.)

Measures of disease occurrence- Incidence

The rate at which new cases of disease occur in a defined population over a period of time. e.g., number of new cases of lung cancer per 100,000 persons per year.

Cumulative Incidence (Risk): Probability that a person develops disease in a given period.

$$CI = \frac{New\ cases}{Population\ at\ risk}$$

Example: new cases of Dengue Fever in one year.

Incidence Rate (Incidence Density): Accounts for different follow-up times.

$$IR = \frac{New\ cases}{Total\ person-time}$$

Example unit: Cases per **1000 person-years**.
Used widely in cohort studies of air pollution and diseases like Ischemic Heart Disease.

Incidence

- Takes into account the factor of time
- Can be used to judge whether there are changes in disease occurrence over time (i.e., trends)
- Can be used to assess the effectiveness of public health interventions (e.g., water supply treatment)
- Most useful in assessing causal associations between exposures and health

Limitations of prevalence (compared to incidence)

- Provides no information on rate of occurrence of new cases
- Limited use for diseases which:
    - have short duration (e.g., colds)
    - are rapidly fatal (e.g., lung cancer).
    - are rare (e.g., most cancers)
- Most useful for persistent diseases (e.g., asthma, psoriasis)

Relationship Between Incidence and Prevalence

- A classic epidemiological relationship:

$$Prevalence = Incidence \times Duration$$

- Implications:

Prevalence increases when:

  - incidence increases
  - disease duration increases

Example chronic diseases such as Diabetes Mellitus have high prevalence because people live long with the disease.

Other measures of disease occurrence

1. Attack Rate

Used mainly in **outbreak investigations**.

$$Attack\ Rate = \frac{New\ cases}{Population\ exposed}$$

Example: food poisoning outbreak at an event causing
Foodborne Illness.

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2. Secondary Attack Rate

Measures **spread among contacts of primary cases**.

Used for diseases like Measles or COVID-19.

3. Mortality Rate

Measures **death occurrence in a population**.

$$Mortality\ Rate = \frac{Deaths}{Population} \times 1000$$

Example: deaths due to Stroke per 1000 population.

4. Case Fatality Rate (CFR)

Indicates **severity of disease**.

$$CFR = \frac{Deaths\ due\ to\ disease}{Total\ cases} \times 100$$

Example: high CFR occurs in diseases like Ebola Virus Disease.

Measures of Association- Relative Risk (RR)

- Relative risk compares risk in exposed vs unexposed groups.

$$RR = \frac{Incidence_{Exposed}}{Incidence_{Unexposed}}$$

RR Value	Meaning
RR = 1	No association
RR > 1	Exposure increases risk

RR < 1	Exposure protective

- Example:
  RR = 1.30 means 30% higher risk.
- Commonly used in cohort studies**.**

Measures of Association- Odds Ratio (OR)

- Used mainly in case-control studies.

$$OR = \frac{Odds_{Exposed\ in\ cases}}{Odds_{Exposed\ in\ controls}}$$

- Interpretation is similar to RR.
- Example: pesticide exposure and Parkinson's Disease.
- When disease is rare:

$$OR \approx RR$$

Measures of Association- Risk Difference (RD)

- Also called **Attributable Risk**.
- Measures **absolute difference in risk** between exposed and unexposed groups.

$$RD = Incidence_{Exposed} - Incidence_{Unexposed}$$

- Example:
  - Incidence exposed = 20 per 1000
  - Incidence unexposed = 10 per 1000

RD= 10/1000

Meaning **10 additional cases due to exposure**.

Measures of Public Health Impact

- These measure **how much disease is caused by a risk factor in the population**.
- They are extremely important in environmental epidemiology.

1. Attributable Fraction (AF)

- Proportion of disease among exposed individuals that is due to exposure.

$$AF = 1 - \frac{1}{RR}$$

Example: RR= 2

$$AF = 1 - \frac{1}{2} = 0.5$$

Meaning **50% of cases among exposed are due to exposure**.

2. Population Attributable Fraction (PAF)

- Proportion of disease in the **whole population** caused by exposure.

$$PAF = \frac{P_e(RR - 1)}{1 + P_e(RR - 1)}$$

- Where: P_e =prevalence of exposure.
- Used to estimate **population burden of environmental risks**.
- Example exposures:
    - Air pollution
    - Smoking
    - Occupational hazards
- Used extensively in the Global Burden of Disease Study.

Distributed Lag Non-Linear Models (DLNM)

- Environmental exposures often have **delayed effects**.
- Example: Air pollution today may affect health **several days later**.
- DLNM captures:
  - **Lag effect** (delay)
  - **Non-linear exposure-response**
- These models are widely used for:
  - Heat waves
  - Air pollution
  - Mortality studies
- Developed by: Antonio Gasparrini.
- Conceptually:

$$Risk = f(Exposure, Lag)$$

Where lag may be:

- 0–7 days
- 0–14 days
- 0–30 days

Applications:

- Daily $PM_{2.5}$ vs mortality
- Temperature vs deaths
- Ozone vs hospital admissions

Advantages:

- Captures delayed health effects
- Handles non-linear exposure response

Implemented in: R programming language package **dlnm**.

Causal Inference in Environmental Epidemiology

Traditional epidemiology often measures association, not causation. Modern studies increasingly apply **causal inference frameworks**.

1. Directed Acyclic Graphs (DAGs)

- DAGs help identify **confounders, mediators, and colliders**.
- Example structure:

- *$PM_{2.5}$ → Inflammation → Cardiovascular Disease*

Confounders:

- Age
- SES
- Smoking

DAGs help determine **which variables should be adjusted for**.

Popular tool: DAGitty.

2. Propensity Score Methods

- Used when exposures are **not randomized**.
- **Steps:**
  - Estimate probability of exposure.
  - Match exposed and unexposed individuals.
  - Estimate causal effect.
- **Methods:**
  - Matching
  - Weighting
  - Stratification

3. Propensity Score Methods

- Used when **unmeasured confounding exists**.

- Example instruments:
  - Wind direction
  - Policy changes
  - Traffic restrictions
- Example study:
  Traffic policy changes affecting pollution levels.

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4. Difference-in-Differences

- Used in **natural experiments**. Example: Air pollution before and after industrial closure.

Causal Inference in Environmental Epidemiology

People are exposed to **multiple pollutants simultaneously**, such as:

- $PM_{2.5}$
- NO_2
- Ozone
- SO_2
- Black carbon

Single pollutant models may give **biased results**. Advanced mixture approaches include:

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1. Weighted Quantile Sum Regression (WQS)

Used for chemical mixtures.

Model:

$$Health = \beta_0 + \beta_1 \sum w_j\, q_j$$

Where:

w_j =weight of pollutant
q_j =quantile of exposure

Advantages: Identifies important pollutants in mixtures.

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2. Bayesian Kernel Machine Regression (BKMR)

Captures:

- Non-linear relationships
- Pollutant interactions

Used in: Environmental mixtures research.

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3. Principal Component Analysis (PCA)

Reduces correlated pollutants into **components**.

Example:
Traffic pollution component:

- NO_2
- CO
- Black carbon

Climate Epidemiology

Climate change is now a **major area of environmental epidemiology**.

Health impacts include:

- Heat-related mortality
- Vector-borne diseases
- Food insecurity
- Air pollution increases
- Mental health effects

Example diseases affected:

- Dengue Fever
- Malaria

Climate variables studied:

- Temperature
- Humidity
- Rainfall
- Extreme weather events

Key climate-health organization:

- Intergovernmental Panel on Climate Change.

Emerging Technologies in Environmental Epidemiology

Wearable Exposure Sensors

Portable devices measure:

- Air pollution
- Noise
- Temperature

Smartphone-based Exposure Tracking

GPS tracks mobility patterns to estimate exposure.

Machine Learning

Used for:

- Exposure prediction
- Health outcome modeling
- Pattern detection

Common algorithms:

- Random Forest
- Gradient Boosting
- Neural networks

Future of Environmental Epidemiology

The field is moving toward:

- High-resolution exposure mapping
- Personal exposure monitoring

- Causal inference methods
- Mixture exposure models
- Climate-health research

Typical Workflow of an Environmental Epidemiology Study

Step 1: Define Research Question

Example: Does $PM_{2.5}$ increase CIMT?

↓

Step 2: Exposure assessment

Use: *Satellite models, Monitoring data, LUR models*

↓

Step 3: Data linkage

Link exposure to individuals based on: *Residence location, Time period*

↓

Step 4: Statistical modeling

Common models: *Linear regression, GAM, DLNM, Mixed models*

↓

Step 5: Sensitivity analysis

Test robustness*: Different exposure windows, Different confounders, Multi-pollutant models*

Major Global Environmental Epidemiology Projects

Important research initiatives include:

1. Global Burden of Disease

Led by:

Institute for Health Metrics and Evaluation.

Estimates disease burden due to environmental risks.

2. ESCAPE Project

European Study of Cohorts for Air Pollution Effects.

3. PURE Study

Large international cohort examining cardiovascular disease risk factors

Key Challenges in Environmental Epidemiology

Exposure Misclassification

Difficulty in measuring exact exposure.

Confounding

Many environmental exposures are correlated with:

- SES
- Lifestyle
- Occupation

Long Latency

Diseases like cancer may appear decades after exposure.

Multiple Exposures

People are exposed to mixtures of pollutants simultaneously.

Example: PM2.5 and cardiovascular disease

- One of the most studied topics.

Long-term exposure to **fine particulate matter** increases risk of:

- Heart attacks
- Stroke

    - Hypertension
    - Atherosclerosis
- Many cohort studies show that even **small increases in PM2.5 lead to higher mortality**.

Importance for Public Health

- Environmental epidemiology helps:
    - Identify harmful exposures
    - Estimate disease burden
    - Guide prevention strategies
    - Develop environmental policies
    - Protect vulnerable populations
- It plays a major role in achieving **sustainable development and healthier environments**.

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