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Forensic Epidemiology: Bridging Population Science, Causal Inference and the Administration of Justice

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Abstract: Background: Epidemiology traditionally investigates the distribution and determinants of health events in populations, whereas forensic science applies scientific evidence to legal questions. Forensic epidemiology lies at their intersection. It uses epidemiological methods to investigate health events with possible legal implications, assess whether an exposure can cause a particular outcome, and estimate whether it probably caused the outcome in a specific individual or group. **Objective:** This narrative review examines the scope, methods and applications of forensic epidemiology, critically evaluates its evidentiary strengths and limitations, and identifies recent developments and priorities for India. **Key findings:** Forensic epidemiology has two major, overlapping applications. The first is medicolegal causal analysis in matters such as toxic exposures, medical negligence, occupational disease, pharmaceutical injury, traffic trauma and mass claims. The second is coordinated public health–law-enforcement investigation of outbreaks, poisonings or mass-casualty events in which deliberate action is suspected. Its central methodological challenge is the transition from population-level association to individual-specific causation. Relative risk, attributable fractions, counterfactual reasoning, Bayesian methods and structured assessment of alternative explanations can assist this transition, but none can mechanically prove causation. Observational bias, exposure misclassification, confounding, base-rate neglect, misuse of probability and differences between scientific and legal standards remain important limitations. India has strong surveillance, forensic medicine and medicolegal systems, but formal training, interoperable data, standardized causal-reporting methods and health–security coordination remain underdeveloped. **Conclusion:** Forensic epidemiology can make medicolegal reasoning more transparent, reproducible and evidence based. It should support—not replace—clinical, pathological, laboratory and investigative evidence. Its future depends on multidisciplinary training, explicit causal frameworks, validated statistical methods, ethical governance and clear communication of uncertainty.

Keywords: Forensic epidemiology; causal inference; medicolegal investigation; outbreak investigation; expert evidence; public health law

INTRODUCTION

Epidemiology is concerned with patterns of disease, injury and exposure in populations. Forensic medicine and forensic science are concerned with questions arising within legal or investigative settings. Forensic epidemiology combines these traditions by applying epidemiological reasoning to adverse health events that may have civil, criminal, regulatory or administrative consequences.

The field has no single universally accepted boundary. In medicolegal practice, forensic epidemiology has been described as a systematic method for evaluating general and specific causation.[1,2] General causation asks whether an exposure is capable of producing an outcome—for example, whether a chemical can cause a particular cancer. Specific causation asks whether that exposure probably caused the disease or injury in the individual whose case is before a court.

A second usage developed through preparedness for bioterrorism and other deliberate events. In this context, forensic epidemiology refers to coordinated application of epidemiological and criminal-investigative methods to determine whether an outbreak, poisoning or environmental release is natural, accidental or intentional.[3,4] Public health investigators focus on identifying cases, controlling exposure and preventing further harm. Law-enforcement investigators focus on intent, attribution, evidence preservation and criminal responsibility. The same event may require both missions simultaneously.

These two applications share a core concern: drawing valid conclusions about cause from incomplete, heterogeneous and potentially contested evidence. Both require disciplined chronology, exposure assessment, comparison with expected patterns, consideration of competing explanations and transparent expression of uncertainty.

Forensic epidemiology is therefore better understood as a problem-oriented interdisciplinary field than as a single technique. Its relevance is increasing because legal systems increasingly encounter complex scientific questions involving pharmaceuticals, environmental pollution, emerging infections, product liability, occupational exposures, disasters and digital health data.

Historical and Conceptual Development

Epidemiological evidence has long influenced legal and public health decisions. Investigations of contaminated water, occupational disease and foodborne outbreaks often identified not only causes of illness but failures of regulation or duty. However, formal use of epidemiology to quantify individual causation developed more recently.

Koehler and Freeman described forensic epidemiology as a means of investigating and quantifying specific causation by integrating epidemiological evidence with case-specific facts.[1] Freeman and Zeegers subsequently emphasized its role in civil and criminal matters and its capacity to express causal conclusions in probabilistic terms suitable for legal fact-finders.[2]

The field differs from ordinary descriptive forensic medicine. A pathologist may identify an anatomical cause of death, while a forensic epidemiologist may examine whether a preceding exposure, collision, treatment delay or institutional failure materially contributed to that death. Similarly, a clinician may diagnose mesothelioma, whereas forensic epidemiology may assess the comparative probability that an occupational exposure, rather than background risk or another exposure, caused the disease.

The discipline also differs from routine epidemiology because the target question is often individual rather than population based. Epidemiology commonly estimates the average effect of an exposure across a defined population. Courts usually ask about a named person, event or defendant. This “group-to-individual” transition is the field’s defining intellectual challenge.

Core Domains of Application

Medicolegal causation

Forensic epidemiology may be applied to alleged medical negligence, delayed diagnosis, adverse drug reactions, occupational disease, toxic torts, product liability, road traffic injuries, disability claims and disputes regarding cause of death.

In medical negligence, the question may be whether delayed treatment materially changed the probability of survival. In occupational litigation, the issue may be whether a worker’s disease is more likely attributable to a workplace exposure than to alternative causes. In pharmaceutical litigation, epidemiological studies may establish whether a drug increases the risk of a claimed outcome, while individual records determine whether the timing, dose and clinical pattern are compatible with that association.

Mass torts create particular challenges. A single industrial release may expose thousands of people at different doses and through different routes. Some conditions may have strong causal links, while others occur commonly in unexposed populations. Forensic epidemiology can help classify exposure groups, estimate excess risk and distinguish population compensation questions from individual diagnosis.

Suspicious outbreaks and deliberate biological events

A naturally occurring outbreak and a deliberately caused outbreak may initially appear identical. Clinical symptoms, laboratory findings and epidemic curves do not independently reveal intent. A compressed point-source epidemic curve, an unusual pathogen or an atypical geographical pattern may raise suspicion, but none is pathognomonic of deliberate release.[3]

Indicators requiring joint assessment may include an unusual agent for the region, an unexpected route of exposure, genetically unusual organisms, simultaneous outbreaks in non-contiguous locations, threats or claims of responsibility, tampering evidence, or disease patterns inconsistent with known ecology. These signals should trigger additional inquiry rather than premature attribution.

Public health and law-enforcement investigations differ in priorities. Public health teams seek rapid case finding, treatment, prophylaxis and source control. Criminal investigators must preserve admissible evidence, establish chain of custody and determine intent and responsibility. Uncoordinated action can compromise both objectives. Delayed information sharing can allow further exposure, while poorly controlled specimen handling can invalidate evidence.

WHO emphasizes that deliberate events require coordinated health and security responses while preserving the respective mandates of epidemiological, humanitarian, criminal and forensic authorities.[4]

Injury, violence and mortality investigation

Forensic epidemiology can identify recurring injury mechanisms across deaths or serious incidents. Analyses of road crashes, firearm injuries, workplace fatalities, custodial deaths or child maltreatment may reveal clusters, institutional patterns or preventable hazards that are not apparent from individual autopsies.

Linked mortality, hospital, police and exposure data can test whether a pattern exceeds expected occurrence. Such analyses may inform criminal investigation, regulatory enforcement, compensation and prevention. However, data linkage can create false matches, and apparent clusters may arise by chance when many locations or outcomes are examined.

Environmental and occupational investigations

Environmental disputes commonly involve long latency periods, mixed exposures and incomplete historical measurements. Forensic epidemiology can reconstruct likely exposure using employment histories, residential data, industrial records, environmental modelling and biological markers.

Occupational examples include asbestos, silica, benzene, pesticides, radiation and ergonomic injury. The investigator must distinguish hazardous exposure, biological plausibility, population-level association and individual attribution. The mere presence of a hazardous substance does not prove that it caused a specific disease; equally, absence of precise historical measurements does not prove absence of meaningful exposure.

General and Specific Causation

A defensible analysis usually begins with general causation. Relevant evidence includes toxicology, clinical observations, mechanistic studies, randomized trials where ethical and feasible, and observational epidemiology. Consistency across methods strengthens inference, but no rigid checklist can substitute for scientific judgement.

Specific causation requires a structured comparison of competing explanations. The investigator should establish:

- whether the person experienced the exposure;
- whether dose, route and duration were sufficient;
- whether the temporal sequence is compatible;
- whether the outcome phenotype matches the known effect;
- whether alternative causes are present; and
- how the probability of the outcome changes under exposure and non-exposure scenarios.

This counterfactual formulation asks: what would probably have happened to this individual, at the relevant time, had the disputed exposure not occurred? The true counterfactual can never be observed. It must be estimated using evidence from comparable populations and individual clinical facts.

Causal inference in forensic medicine has historically ranged from intuitive judgement to probabilistic methods. Reviews have found no universally applicable methodology, but structured probabilistic approaches offer greater transparency in complex cases.[5]

Epidemiological Measures in Legal Causation

Relative risk

Relative risk compares outcome risk in exposed and unexposed groups. A relative risk above 1 indicates a positive association. In some legal reasoning, a relative risk greater than 2 has been interpreted as implying that more than half of cases among exposed persons are attributable to the exposure.

This interpretation is frequently oversimplified. It applies only under restrictive assumptions: the study population must be sufficiently comparable to the individual, bias and confounding must be adequately controlled, exposure must be similarly defined, and no strong individual-specific evidence should alter the probability. A relative risk below 2 does not exclude causation in a particular person, and a relative risk above 2 does not prove it.

Attributable fraction among the exposed

Where a causal relative risk is valid, the attributable fraction among exposed persons may be estimated as:

(RR – 1) / RR

This expresses the proportion of cases among exposed individuals statistically attributable to the exposure. It is a population quantity, not a direct probability that one named individual's disease was caused by the exposure.

Individual susceptibility, competing risks, exposure intensity and disease subtype may make the person's probability higher or lower than the population average.

Odds ratios and hazard ratios

Odds ratios approximate relative risks only when outcomes are uncommon under relevant conditions. Hazard ratios compare instantaneous event rates over time and should not automatically be interpreted as risk ratios or probabilities of causation.

Experts must explain what a measure actually represents. Presenting an odds ratio, hazard ratio and risk ratio as interchangeable can materially mislead a court.

Bayesian reasoning

Bayesian reasoning combines a prior probability with the likelihood of observed evidence to produce an updated probability. It is useful when multiple independent or conditionally dependent pieces of evidence must be integrated.

The method's strength is explicitness: assumptions are stated rather than concealed. Its weakness is sensitivity to the selected prior probabilities and likelihood estimates. Bayesian outputs can appear falsely precise when inputs are uncertain or dependent.

Likelihood ratios are often preferable to declaring an ultimate probability. They describe how much more likely the evidence is under one causal hypothesis than another. The legal decision-maker can then integrate that scientific evidence with other facts.

Table 1. Major Components of a Forensic Epidemiological Investigation

Component	Principal question	Main evidence and methods	Common error	Recommended safeguard
Case definition	Who qualifies as affected?	Clinical criteria, laboratory results, time, place and person	Changing definitions without documenting their effect	Use explicit, graded definitions and conduct sensitivity analyses
Exposure assessment	Did exposure occur, at what dose and by which route?	Records, interviews, environmental data, biomarkers and modelling	Treating presence of a hazard as proof of causal exposure	Reconstruct timing, route, intensity and uncertainty
General causation	Can the exposure cause the outcome?	Epidemiology, toxicology, clinical evidence and mechanisms	Selecting only studies supporting the desired conclusion	Use systematic, balanced evidence appraisal
Specific causation	Did exposure probably cause this individual's outcome?	Individual history, comparative risks and alternative-cause analysis	Mechanically applying a population relative risk	Assess individual comparability and competing explanations
Temporal	Did cause	Timelines,	Assuming temporal	Compare timing with

analysis	precede effect within a plausible interval?	incubation periods and latency distributions	sequence alone proves causation	known biological ranges
Cluster analysis	Is the event frequency or pattern unusual?	Baseline rates, spatial–temporal statistics and surveillance data	Post hoc boundary selection and multiple testing	Predefine hypotheses and assess chance clustering
Deliberate-event assessment	Is intentional action plausible?	Epidemiology, intelligence, environmental and forensic evidence	Treating an unusual outbreak as proof of attack	Maintain natural, accidental and deliberate hypotheses
Laboratory investigation	What agent or toxicant is present?	Culture, sequencing, toxicology and chemical analysis	Contamination, sample substitution or undocumented handling	Maintain chain of custody and quality assurance
Causal quantification	How strongly does evidence favour one explanation?	Relative risks, attributable fractions, Bayesian or likelihood methods	False precision and confusion of association with causation	Report assumptions, uncertainty intervals and sensitivity analyses
Alternative explanations	Could another factor better explain the outcome?	Differential diagnosis, background rates and competing exposures	"Differential aetiology" by exclusion without positive evidence	Compare alternatives using the same evidentiary standard
Expert reporting	What can reasonably be concluded?	Structured written opinion and visual presentation	Advocacy, jargon and categorical claims unsupported by data	Separate facts, assumptions, analysis and opinion
Public health response	How can further harm be prevented?	Control measures, communication and surveillance	Delaying action until criminal attribution is resolved	Separate immediate control from later attribution

Evidence Preservation and Chain of Custody

Forensic epidemiology may generate information for public health action and legal proceedings. Specimens, environmental samples, electronic records and interview data must therefore be collected in ways that preserve both scientific quality and evidentiary integrity.

A chain of custody records who collected, handled, transferred, stored and analysed each item. Public health laboratories routinely prioritize rapid diagnosis; forensic laboratories additionally require tamper-evident handling, authentication and documentation suitable for judicial scrutiny. Joint protocols should be established before an emergency.

Epidemiological databases may themselves become evidence. Changes to case definitions, data cleaning decisions, excluded observations and analytical code must be documented. Reproducible analysis is particularly important when conclusions affect criminal responsibility or large compensation claims.

Genomic sequencing can link cases and identify transmission relationships, but genetic similarity rarely proves direct transmission between two persons. Unsampled intermediaries, common sources and incomplete sequence diversity must be considered. Investigators should resist converting phylogenetic proximity into categorical legal attribution.

Standards of Proof and Communication

Scientific and legal standards answer different questions. Epidemiology seeks estimates that remain valid under uncertainty. Courts must reach decisions under defined burdens of proof, such as balance of probabilities in many civil matters or proof beyond reasonable doubt in criminal cases.

An epidemiologist should not convert a scientific confidence interval directly into a legal standard. A 95% confidence interval does not mean that there is a 95% probability that the causal claim is true. Statistical significance does not establish legal causation, and non-significance does not prove absence of effect.
Expert reports should distinguish:

- established facts;
- assumed facts supplied by others;
- scientific evidence;
- analytical methods;
- uncertainties and limitations; and
- the expert's final opinion.

Probability should be expressed in language that remains consistent and understandable. Terms such as "possible," "probable" and "highly probable" are used inconsistently unless linked to defined ranges or clearly explained reasoning. Excessive numerical precision can be as misleading as vague language.
The expert's duty is to assist the court, not to advocate for the party retaining them. Selective citation, unacknowledged conflicts of interest and failure to disclose alternative explanations undermine both science and justice.

Public Health Significance

Forensic epidemiology strengthens public health by converting individual medicolegal events into population-level prevention. A cluster of poisoning deaths may reveal an adulterated product; repeated occupational claims may expose unsafe industrial practices; a pattern of deaths following delayed treatment may identify systemic failure.
The field also improves accountability. Public health recommendations carry greater weight when causal analysis is transparent and supported by reproducible evidence. Conversely, forensic investigation benefits from epidemiological understanding of background rates, expected variation and disease transmission.
In suspected deliberate events, rapid cooperation can prevent deaths while protecting the integrity of criminal investigation. Public reassurance also depends on credible explanation. Premature claims of attack may generate panic and stigma, while delayed acknowledgement of a genuine threat may prolong exposure.

Recent Advances

The most important methodological advance is wider use of explicit causal inference. Directed acyclic graphs can clarify assumptions about confounding, mediation and selection. Counterfactual frameworks distinguish the effect of an exposure from mere correlation.
Bayesian networks and probabilistic graphical models can integrate clinical, epidemiological and forensic evidence. These methods are particularly useful where several causal pathways and uncertain observations coexist. Their results remain dependent on model structure and input quality and should be accompanied by sensitivity analysis.
Genomic epidemiology has transformed outbreak investigation. Whole-genome sequencing can identify clusters, distinguish strains and support reconstruction of transmission. Wastewater surveillance, digital syndromic systems and community-based reporting can detect unusual events earlier. These tools increase sensitivity but may also produce signals of uncertain clinical or legal meaning.
Artificial intelligence may assist record linkage, pattern detection and document review. However, opaque algorithms are problematic in legal contexts because conclusions must be explainable and contestable. Training-data bias, automation bias and false matches can affect individuals disproportionately.
A further advance is the recognition that deliberate events may involve not only biological and chemical agents but cyberattacks, disinformation and disruption of health infrastructure. WHO now frames these threats within a broader health–security interface.[4]

Challenges and Limitations

The largest limitation is the ecological and probabilistic nature of much epidemiological evidence. Population associations do not automatically establish what happened to an individual.

Observational studies may be affected by confounding, recall bias, selection bias and exposure misclassification. Published studies may not reflect the claimant's age, dose, genetics, comorbidities or exposure context. Meta-analysis can increase precision but cannot remove systematic bias in the underlying studies.

Forensic questions frequently arise after an event, encouraging post hoc selection of hypotheses, geographical boundaries or comparison groups. Apparent clusters may result from random variation, especially when many outcomes are searched.

Another problem is adversarial distortion. Each party may retain experts who select different evidence, assumptions and methods. Formal checklists can improve transparency but cannot eliminate judgement.

Privacy and civil-liberty concerns are increasingly important. Linking health, police, genomic, location and digital data may improve investigation while exposing individuals and communities to surveillance or discrimination. Use of public health data for law enforcement requires clear legal authority, proportionality and governance.

The field also risks overexpansion. Not every medicolegal case requires complex probabilistic analysis. A direct and well-documented cause may be established through clinical or pathological evidence alone. Sophisticated modelling should be reserved for questions where it adds genuine explanatory value.

Indian Perspective

India has several systems relevant to forensic epidemiology: the Integrated Disease Surveillance Programme and Integrated Health Information Platform, medical-college departments of forensic medicine, public health laboratories, poison-control and toxicology services, police forensic laboratories and disaster-management structures. The IHIP increasingly supports near-real-time reporting and investigation of unusual disease events, including community reporting.[6]

However, these systems often operate in parallel. Surveillance data may not be routinely linked with autopsy, police, environmental, occupational or toxicological data. Joint health–law-enforcement protocols for suspicious outbreaks are less institutionalized than conventional epidemic-response procedures.

India's Bharatiya Sakshya Adhiniyam, effective from July 1, 2024, recognizes expert opinion and the grounds supporting such opinion as relevant evidence.[7] This creates an important context for transparent epidemiological expert testimony. An expert's conclusion must be accompanied by the scientific basis, assumptions and limitations from which it was derived.

The Bharatiya Nagarik Suraksha Sanhita, also effective from July 1, 2024, modernizes criminal procedure and strengthens the role of forensic investigation in serious offences.[8] Greater use of forensic evidence will increase demand for specialists capable of interpreting population data, causation and uncertainty, not merely laboratory results.

Potential Indian applications include industrial disasters, food and alcohol poisoning, occupational lung disease, pesticide exposure, deaths during heatwaves, road-traffic injury, pharmaceutical adverse events, custodial mortality, medical negligence and suspicious infectious-disease clusters.

The Bhopal gas disaster remains a powerful historical example of the difficulties of reconstructing exposure, identifying long-term effects, defining affected populations and attributing individual outcomes after a mass toxic release. Contemporary preparedness should establish baseline environmental and health data before disasters occur.

India needs formal forensic-epidemiology training within MD Community Medicine, MD Forensic Medicine, epidemiology programmes, public health laboratories and police academies. Joint exercises should include outbreak control, scene security, specimen collection, chain of custody, risk communication and legal reporting.

Policy Implications

National and state protocols should define when a health event requires joint epidemiological and criminal investigation. Notification thresholds should be sensitive without treating every unusual outbreak as deliberate.

Multidisciplinary rapid-response teams should include epidemiologists, clinicians, microbiologists, toxicologists, forensic specialists, veterinarians, environmental experts and law-enforcement officers. Roles, command structures and data-sharing rules should be agreed before emergencies.

Standard formats are needed for causal-analysis reports in medical negligence, occupational disease, toxic exposure and mass claims. These should require explicit discussion of general causation, specific causation, alternative explanations and uncertainty.
Laboratory strengthening should include molecular epidemiology, broad toxicological screening, biosafety and legally defensible sample handling. Digital systems should retain audit trails and permit reproducible analysis.
Courts and tribunals would benefit from training in basic epidemiological measures, particularly the differences between relative risk, attributable fraction, statistical significance and probability of individual causation.

Future Directions
Research should compare different methods of specific-causation assessment and determine whether they produce reproducible conclusions when applied by independent experts.
Validated reporting standards are needed for forensic epidemiological opinions. These should resemble scientific reporting guidelines by requiring transparent exposure definitions, source selection, causal assumptions and sensitivity analyses.
India should develop linked sentinel datasets combining hospital, mortality, autopsy, toxicology, environmental and police information under strong privacy safeguards. Such systems could identify poisoning clusters, unsafe products and preventable injury patterns.
Genomic and digital methods require ethical and legal frameworks that distinguish public health use from criminal attribution. Evidence generated for outbreak control should not automatically be repurposed for prosecution without lawful authority and due process.
Artificial intelligence should remain an analytical aid rather than an autonomous expert. Models used in legal proceedings must be explainable, independently validated and open to challenge.
Finally, forensic epidemiology should retain its preventive orientation. The ultimate purpose is not only to allocate blame or compensation but to identify why harm occurred and prevent recurrence.

CONCLUSION

Forensic epidemiology brings the comparative, probabilistic and population-based methods of epidemiology into legal and investigative settings. It provides a disciplined approach to questions that clinical judgement, laboratory testing or pathology alone may not resolve.
Its central contribution is the separation of general causation from specific causation and the transparent evaluation of competing explanations. Relative risks, attributable fractions and Bayesian methods can inform this process, but none provides an automatic formula for legal proof.
The field is equally important in suspicious outbreaks, where public health and law-enforcement teams must control harm while determining whether an event was natural, accidental or deliberate.
India has substantial surveillance, forensic and legal infrastructure on which to build. The transition to new criminal and evidence laws, expansion of digital surveillance and increasing scientific complexity make formal development of forensic epidemiology particularly timely.
Used carefully, forensic epidemiology can improve scientific credibility, judicial fairness and public health prevention. Used mechanically or selectively, it can create false certainty. Its defining professional obligation is therefore not simply to calculate probabilities, but to explain honestly what the evidence can—and cannot—establish.

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