RESEARCH ARTICLE

SOILS IN FORENSIC ANALYSIS: A REVIEW

Subhadeep Karak[1], Janakirama Suresh KG[1], Tarik Mitran[1], Sujatha G.[1], Rajiv Kumar[2], Sreenivas K.[3] and Umesh Thapa[4]

1.   Soil and Land Resources Assessment Division, Soil Resources and Land Use Mapping and Monitoring Group, National Remote Sensing Centre, Hyderabad, India.
2.   Soil Resources and Land Use Mapping and Monitoring Group, National Remote Sensing Centre, Hyderabad, India.
3.   Remote Sensing Application Area, National Remote Sensing Centre, Hyderabad, India.
4.   Faculty of Horticulture, Bidhan Chandra Krishi Viswavidyalaya, West Bengal, India.

……....

Manuscript Info	*Abstract*
……………………..	………………………………………………………………
	This review article highlights article highlights the crucial role of soil in forensic investigations, showcasing its ability to connect suspects, victims, and crime scenes. In the present scenario, the importance of this work is underscored by the increasing complexity of criminal activities and the growing need for precise forensic methods. As environmental conditions and land use patterns change, understanding soil characteristics and their forensic applications becomes even more crucial. Through advanced analysis techniques like spectroscopy and DNA profiling, soil becomes a valuable tool for solving crimes, tracing geographical origins, and providing crucial evidence, reinforcing its importance in modern forensic science. This review showcases soil as a powerful, often overlooked tool in solving crimes and bringing justice, despite challenges like soil variability and contamination.

………....

1. Introduction

Soil, often seen as just dirt, plays a critical role in forensic science, helping solve crimes and uncovering hidden truths. The ubiquity and transferability of soil to objects or persons has become a powerful tool in investigations **(Dawson et al., 2010)**. Even though soil might seem unimportant at first glance, it holds a wealth of valuable information about a crime scene. By examining soil samples from crime scenes, forensic scientists can connect suspects, victims, and locations, providing crucial evidence. In Roman times, soil and rocks found in the hooves of horses were reputedly used to trace their origins and travel paths **(Murray, 2011).** This ancient practice highlights the longstanding significance of soil analysis in tracing and solving mysteries. In modern forensic science, when investigating crime scenes or examining evidence, soil components like mixture of inorganic (geological), organic (biological), and organo-mineral components are discovered and gathered using hand lenses or light microscopes **(Dawson et al., 2015)**. To ensure that soil samples are relevant during an investigation, they must be carefully collected and handled using recognized procedures, then evaluated by a soil researcher with forensic science knowledge **(Dudley, 1975)**. Forensic soil science involves the use of soil science, particularly investigations involving soil morphology, soil mapping (aided by soil texture maps and spatially stored soil data), minerals, chemistry, geophysics, and cell biology, to solve legal issues, problems, or theories **(Chaperlin, 1983)**.This article explores the importance of soil in forensic investigations, detailing how scientists analyze soil to solve crimes and

Corresponding Author:- Subhadeep Karak
Address**:** Soil and Land Resources Assessment Division, Soil Resources and Land Use Mapping and Monitoring Group, National Remote Sensing Centre, Hyderabad, India.

bring justice. Through meticulous analysis of soil samples, forensic scientists can uncover hidden evidence, trace geographical origins, and connect suspects to crime scenes.

2. The Foundation of Forensic Soil Analysis

Soil is a complex mixture of inorganic minerals, organic materials, and biological matter, varying greatly across different locations. This variability makes soil a unique and powerful tool in forensic investigations. The principle behind forensic soil analysis is based on Locard's Exchange Principle **(Locard, 1930)**, which states that every contact leaves a trace. When people or objects come into contact with soil, they transfer tiny particles that can be analyzed to provide clues about where they have been.

Soil pedology, the scientific study of soils in their natural environment, is pivotal in forensic analysis. Each location exhibits a unique soil profile characterized by distinct physical, chemical, and biological properties. Pedology facilitates the identification of these unique soil characteristics, including color, texture, structure, and mineral content **(Correa et al., 2018)**. This enables the comparison of soil samples from a crime scene with those from a suspect's clothing, shoes, or vehicle, potentially establishing a link between an individual or object and a specific location.

3. Tracing Origins: Soil as a Geographical Identifier

Soil serves as a powerful geographical identifier in forensic science. Soil formation, or pedogenesis, is influenced by factors such as parent material, climate, topography, vegetation, and human activity. These factors create unique soil profiles in different regions, making soil a "fingerprint" of the environment.
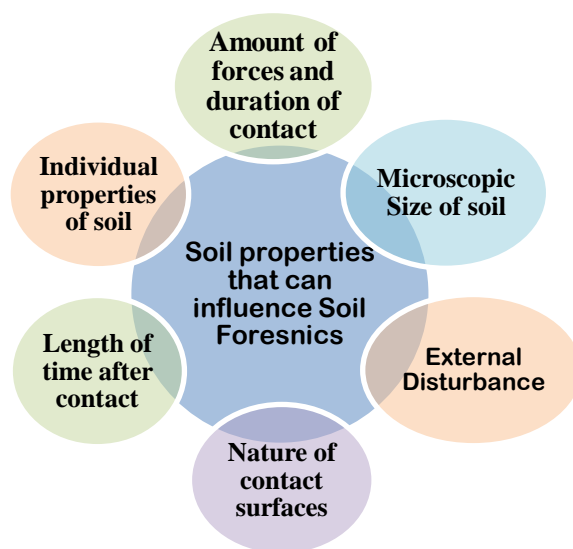

Fig. 1:- Factors influencing Soil Forensic Analysis

Forensic soil analysis compares soil samples from crime scenes with reference samples from known locations. By examining characteristics like mineral composition, organic content, texture, color **(Sugita et al., 1996)**, and microorganisms, scientists can infer the geographical origin of a soil sample. This helps investigators link crime scenes to specific areas, providing crucial evidence in criminal cases. Sometimes, soil pedology considers the influence of environmental conditions, such as moisture, temperature, and pH, which can affect the decomposition of organic material **(Speruda et al., 2022)**.

Technological advancements have enhanced the capabilities of forensic soil analysis. Techniques like hyperspectral imaging, satellite imagery, and geographic information systems (GIS) allow scientists to assess soil properties over large areas and create detailed maps **(Ruffell et al., 2010)**. These tools help forensic scientists identify and compare soil samples with greater accuracy.

4. Uncovering Hidden Evidence: Soil as a Trace Material

Soil is a reservoir for trace materials, including DNA, fibers, botanical remains, and microscopic particles, that can provide valuable insights into a crime. When individuals come into contact with soil, they leave behind traces that forensic scientists can analyze to gather evidence. According to **Grieve (2005)**, soil trace evidence can provide critical information about the movements and activities of suspects and victims, often yielding insights that other forms of evidence cannot.

Techniques such as microscopy, spectroscopy, and DNA profiling are used to examine trace materials in soil samples. Microscopic analysis reveals particles like pollen grains, plant fragments, insect remains, and mineral grains, which can provide clues about the environment and activities associated with a soil sample.

Spectroscopic techniques, such as infrared and Raman spectroscopy, offer insights into the chemical composition of trace materials and help to identify organic compounds, minerals, and other substances present in soil samples **(Chauhan et al., 2018)**. DNA profiling, a powerful tool in forensic science, enables scientists to extract genetic material from soil and link it to individuals or species of interest **(Young et al., 2021)**.

Fig. 2:- Microscopic analysis of soil sample

5. Methodologies of Soil Analysis

Forensic examination of soil is not only concerned with the analysis of naturally occurring rocks, minerals, vegetation, and animal matter but also includes the detection of such manufactured materials such as ions from synthetic fertilizers and from different environments as environmental artifacts whose presence may impart soil with characteristics that will make it unique to a particular location **(Cengiz et al., 2003)**. Forensic soil analysis encompasses a range of techniques to evaluate soil samples, from basic visual examinations to advanced chemical and biological analyses **(Fitzpatrick & Fitzpatrick, 2019)**. These methodologies include visual examination, chemical analysis, mineralogical analysis, and biological analysis.

5.1 Visual Examination

Visual examination involves inspecting soil samples under a microscope to observe physical characteristics like texture, color, and structure. Microscopic analysis provides detailed insights into the composition and morphology of soil particles **(Sugita et al., 2001)**, helping identify minerals, plant fragments, and other microscopic components.
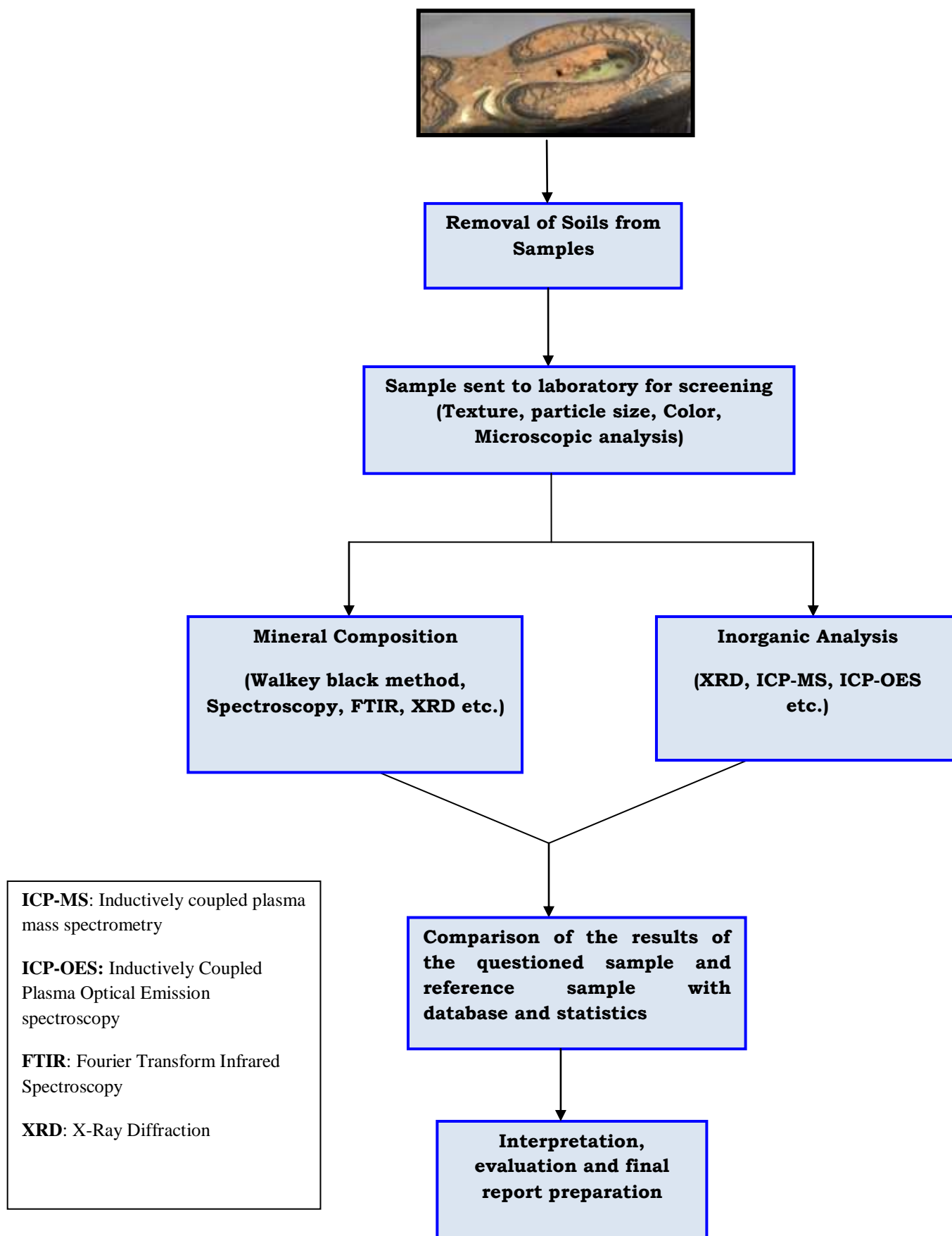
Removal of Soils from Samples

↓

Sample sent to laboratory for screening (Texture, particle size, Color, Microscopic analysis)

Mineral Composition

(Walkey black method, Spectroscopy, FTIR, XRD etc.)

Inorganic Analysis

(XRD, ICP-MS, ICP-OES etc.)

ICP-MS: Inductively coupled plasma mass spectrometry

ICP-OES: Inductively Coupled Plasma Optical Emission spectroscopy

FTIR: Fourier Transform Infrared Spectroscopy

XRD: X-Ray Diffraction

Comparison of the results of the questioned sample and reference sample with database and statistics

↓

Interpretation, evaluation and final report preparation

Fig.3: Flowchart of Methodologies of Forensic Soil Analysis

5.2 Chemical Analysis

Chemical analysis characterizes the chemical composition and properties of soil samples. The Microwave digestion technique followed by inductively coupled plasma-atomic emission spectroscopy (ICP-AES) helps to determine the content of heavy metals in sediments and soils **(Sandroni et al., 2003)**. Techniques such as wet chemistry, elemental analysis, and spectroscopy are used to identify specific chemical constituents. For example, X-ray fluorescene (XRF) spectroscopy determines the elemental composition, while Fourier-transform infrared (FTIR) spectroscopy provides information about organic compounds **(Pye et al., 2006)**.

5.3 Mineralogical Analysis

Mineralogical analysis focuses on identifying and characterizing mineral phases in soil samples. Techniques like X-ray diffraction (XRD) and scanning electron microscopy (SEM) analyze the crystalline structure and mineral composition, revealing information about the geological origin and environmental conditions associated with the soil **(Pye et al., 2007)**

5.4 Biological Analysis

Biological analysis identifies microorganisms, plant material, and other biological components in soil samples. Techniques such as DNA sequencing, polymerase chain reaction (PCR), and microscopy analyze the biological content, helping trace sources of contamination and assess microbial activity **(Young et al., 2014)**. This analysis provides insights into the ecological context and potential sources of biological evidence.

6. Case Studies: Soil's Role in Criminal Investigations

6.1 The Atlanta Child Murders: A Case Study

(As reported by FBI News, February 7, 2014 https://www.fbi.gov/news/stories/-serial-killers-part-5-wayne-williams-and-the-atlanta-child-murders)

Background: In the late 1970s and early 1980s, Atlanta, Georgia, was gripped by a series of tragic murders primarily targeting African-American children and young adults. The victims were often found in remote areas, making it difficult for investigators to establish clear links between the crime scenes and the perpetrator.

Forensic Soil Analysis: Soil analysis emerged as a pivotal tool in these investigations. Forensic soil scientists collected soil samples from various crime scenes and examined their geological characteristics, such as mineral content, color, texture, and composition. The analysis revealed that several samples from different crime scenes shared unique and distinct geological traits, suggesting a common origin.

Linking Crime Scenes: By comparing the soil samples from the crime scenes with reference samples from different locations, investigators could narrow down potential sites where the perpetrator might have disposed of the bodies. This process involved detailed mapping of the geological landscape around Atlanta and identifying specific areas with matching soil profiles.

Arrest and Conviction: The forensic evidence eventually led investigators to focus on Wayne Williams, a local man who was later linked to several of the murders. Soil samples taken from Williams' car, home, and other belongings matched the distinct soil profiles found at the crime scenes. This evidence, combined with other investigative findings, led to Williams' arrest and conviction for two of the murders. Although Williams was only convicted of two murders, the evidence suggested his involvement in many more, providing closure to numerous grieving families.

6.2 The Lindbergh Kidnapping Case: A Case Study
(As reported by FBI News on their "History of famous cases and criminals https://www.fbi.gov/history/famous-cases/lindbergh-kidnapping)

Background: In 1932, the kidnapping of Charles Lindbergh Jr., the infant son of famous aviator Charles Lindbergh, became a national sensation. The baby was taken from the Lindbergh home, and a ransom note was left behind. Despite the payment of the ransom, the child was found dead weeks later.

Forensic Soil Analysis: During the investigation, forensic scientists turned to soil analysis to track the kidnapper's movements and identify the ransom drop site. Soil samples from the ransom drop site were collected and analyzed

for their mineral and organic content. These samples were then compared to reference soil samples from various locations.

Identifying the Ransom Drop Site: The detailed analysis allowed scientists to pinpoint the specific location where the ransom money had been buried. The soil characteristics at the ransom site matched those found on the kidnapper's belongings and the areas he frequented.

Conviction: The forensic evidence, combined with other investigative efforts, led to the identification and arrest of Bruno Hauptmann. Soil analysis played a crucial role in corroborating the evidence against Hauptmann, including the ransom money found in his possession. Hauptmann was ultimately convicted of the kidnapping and murder of Charles Lindbergh Jr., highlighting the importance of forensic soil analysis in solving the case.

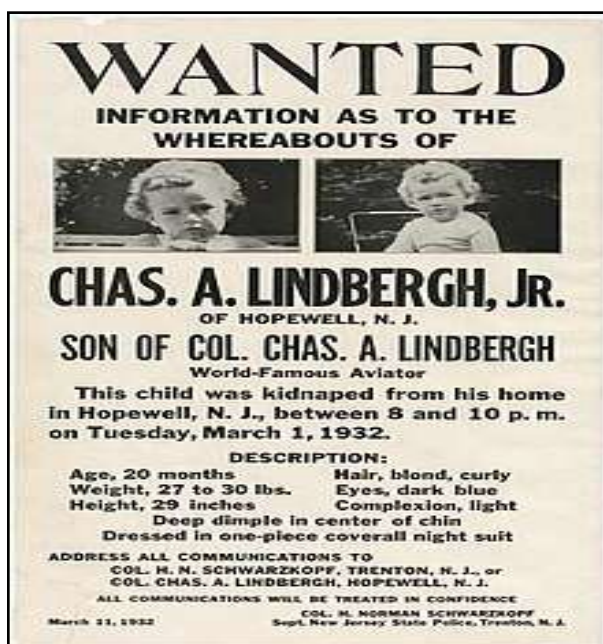**Fig. 4**: Prime accused with the letter of FBI
Source: https://www.fbi.gov/news/stories

Fig 5: Missing advertisement of the child
Source:https://en.wikipedia.org/wiki/Lindbergh_kidnapping

6.3 The Yorkshire Ripper Case: A Case Study
 (As reported by BBC News, https://www.bbc.com/news/av/uk-34972009)
Background: In the late 1970s and early 1980s, northern England was terrorized by the Yorkshire Ripper, who committed a series of brutal murders. The perpetrator targeted women, and the police struggled to catch him due to the random nature of the attacks and the lack of clear evidence.
Forensic Soil Analysis: Forensic soil analysis became a critical component of the investigation. Soil samples were collected from various crime scenes and examined for their unique profiles. The analysis focused on identifying specific soil characteristics such as particle size, composition, and the presence of unique minerals or organic materials.
Linking the Perpetrator to the Crime Scenes: Soil samples taken from Peter Sutcliffe's clothing, footwear, and vehicle were compared to the samples from the crime scenes. The unique soil profiles associated with Sutcliffe's movements provided crucial evidence. For instance, soil found on Sutcliffe's vehicle matched the soil from the locations where several victims had been found.
Conviction: The soil evidence, along with witness testimonies and other forensic findings, established Sutcliffe's presence at multiple crime scenes. This evidence played a significant role in his arrest and subsequent conviction for the murders. Sutcliffe was convicted of murdering 13 women and attempting to murder 7 others, bringing an end to his reign of terror.

7. Challenges and Limitations

While soil analysis is invaluable in forensic investigations, it faces several challenges and limitations. Understanding these hurdles is crucial for ensuring the accurate interpretation and application of soil analysis in criminal investigations.

Soil Variability
Soil properties vary significantly even within small areas, complicating the comparison of samples. This variability can make it difficult to establish distinct soil profiles, especially in regions with complex soil compositions.

Lack of Standardization
There is a lack of standardized protocols for soil analysis in forensic investigations. Different laboratories may use varying methods, leading to inconsistencies in sample collection, analysis, and interpretation. Standardized protocols are needed to ensure reliable and reproducible results.

Reference Databases
Comprehensive reference databases containing soil profiles from various locations are essential for comparison. However, these databases may be lacking or incomplete, limiting their utility for forensic analysis.

Contamination and Preservation
Soil samples collected from crime scenes are susceptible to contamination from various sources, compromising their integrity as forensic evidence **(Croft et al., 2004)**. Proper collection, handling, and preservation are crucial to minimize contamination and maintain evidentiary value.

8. Future Directions and Innovations

The future of forensic soil analysis holds great promise, driven by advancements in technology and interdisciplinary collaboration. **Martínez et al. (2017)** highlighted current trends and future prospects in forensic soil analysis, emphasizing the integration of new technologies and methodologies to improve accuracy and reliability.

Advances in Analytical Techniques
Emerging techniques like isotopic analysis, nanoparticle tracking, and hyperspectral imaging are revolutionizing soil analysis **(Edelman et al., 2012)**. Isotopic analysis provides insights into the geographic origin and environmental history of soil samples, while nanoparticle tracking detects trace materials at the nanoscale. Hyperspectral imaging offers enhanced capabilities for identifying soil properties.

Integration of Big Data and Machine Learning
Big data analytics and machine learning algorithms are transforming soil analysis. These tools process large datasets, identify patterns, and extract meaningful insights. Machine learning helps forensic scientists make informed decisions and uncover hidden correlations within soil data.

Portable and Field-Deployable Technologies
Portable instruments like XRF analyzers, handheld Raman spectrometers, and mobile DNA sequencers enable rapid on-site analysis of soil samples **(Woods et al., 2014).** These technologies provide real-time data, supporting field operations and investigative decisions.

Forensic Geo-informatics and Spatial Analysis
Geographic information systems (GIS), remote sensing technologies, and spatial statistics enhance the spatial representation of soil data. These tools create detailed maps and models of crime scenes, soil distributions, and environmental contexts, providing valuable insights for forensic analysis **(Krekeler et al., 2023)**

Interdisciplinary Research and Collaboration
Collaboration between scientists, law enforcement agencies, and legal professionals drives innovation in forensic soil analysis. Interdisciplinary research fosters the development of advanced techniques and methodologies, enhancing the field's capabilities.

Conclusion:-

Soil plays a crucial role in forensic science, helping solve crimes and bring justice. Through meticulous analysis of soil samples, forensic scientists can uncover hidden evidence, trace geographical origins, and connect suspects to crime scenes. Despite challenges like soil variability and contamination, advancements in technology and interdisciplinary collaboration continue to enhance the capabilities of forensic soil analysis. By integrating soil science with forensic methodologies, this work not only advances the field but also reinforces the importance of soil as a vital component of forensic investigations, paving the way for more precise and reliable criminal justice outcomes.

References:-

1. Chaperlin, K., & Howarth, P.S. (1983). Soil Comparison by Density Gradient Method-A Review and Evaluation. Forensic Sci. Int., **23(2-3**), 93-303.
2. Cengiz, S., Karaca, A.C., Çakır, İ., Üner, H.B., & Sevindik, A. (2004). SEM–EDS analysis and discrimination of forensic soil. **Forensic Science International**, **141(1)**, 33-37. https://doi.org/10.1016/j.forsciint.2003.12.006
3. Chauhan, R., Kumar, R., & Sharma, V. (2018). Soil forensics: a spectroscopic examination of trace evidence. Microchemical Journal, 139, 74-84.
4. Corrêa, R. S., Melo, V. F., Abreu, G. G. F., Sousa, M. H., Chaker, J. A., & Gomes, J. A. (2018). Soil forensics: how far can soil clay analysis distinguish between soil vestiges?. Science & Justice, **58(2)**, 138-144.
5. Croft, D.J., & Pye, K. (2004). Multi-technique comparison of source and primary transfer soil samples: An experimental investigation. **Science & Justice**, **44(1)**, 21-28. https://doi.org/10.1016/S1355-0306(04)71681-0.
6. Dawson, L. A., & Hillier, S. (2010). Measurement of soil characteristics for forensic applications. Surface and Interface Analysis: An International Journal devoted to the development and application of techniques for the analysis of surfaces, interfaces and thin films, **42(5),** 363-377.
7. Dawson, L. A., & Mayes, R. W. (2015). Criminal and environmental soil forensics: soil as physical evidence in forensic investigations. In Introduction to environmental forensics (pp. 457-486). Academic Press.
8. Dudley, R.J. (1975). The use of colour in discrimination between soils. J. Forensic Sci. Soc. **15(3)**, 209-218.
9. Edelman, G.J., Gaston, E., van Leeuwen, T.G., Cullen, P.J., & Aalders, M.C.G. (2012). Hyperspectral imaging for non-contact analysis of forensic traces. **Forensic Science International**, **223(1–3)**, 28-39. https://doi.org/10.1016/j.forsciint.2012.09.012.
10. Fitzpatrick, R. W., & Fitzpatrick, R. W. (2019). Introduction to forensic soil science, CRC Press.
11. Grieve, M. C. (2005). Soil evidence: using soil trace evidence in forensic investigations, CRC Press.
12. Krekeler, M. P., Burke, M., Allen, S., Sather, B., Chappell, C., McLeod, C. L., ... & Fackey, D. (2023). A novel hyperspectral remote sensing tool for detecting and analyzing human materials in the environment: a geoenvironmental approach to aid in emergency response. Environmental Earth Sciences, **82(4)**, 109. https://doi.org/10.1007/s12665-023-10761-1.
13. Locard, E. (1930). The analysis of dust traces. Part I. American Journal of Police Science, **1(3)**, 276-298.
14. Martínez, S., Delgado, L., Alonso, E., & García, A. (2019). Forensic soil analysis: a review of current trends and future prospects. Soil Systems, **1(2)**, 20.
15. Murray, O. (2011). The Cambridge Illustrated History of Ancient Greece and Rome, 128-155, Cambridge University Press.
16. Pye, K., Blott, S.J., & Wray, D.S. (2006). Elemental analysis of soil samples for forensic purposes by inductively coupled plasma spectrometry — precision considerations. **Forensic Science International**, **160(2–3),** 178-192. https://doi.org/10.1016/j.forsciint.2005.09.012.
17. Pye, K., & Croft, D. (2007). Forensic analysis of soil and sediment traces by scanning electron microscopy and energy-dispersive X-ray analysis: An experimental investigation. **Forensic Science International**, **165(1)**, 52-63. https://doi.org/10.1016/j.forsciint.2006.03.001.
18. Ruffell, A. (2010). Forensic pedology, forensic geology, forensic geoscience, geoforensics and soil forensics. Forensic Science International, **202(1-3)**, 9-12.
19. Sandroni, V., Smith, C.M.M., & Donovan, A. (2003). Microwave digestion of sediment, soils and urban particulate matter for trace metal analysis. **Talanta**, **60(4)**, 715-723. https://doi.org/10.1016/S0039-9140(03)00131-0.
20. Speruda, M., Piecuch, A., Borzęcka, J., Kadej, M., & Ogórek, R. (2022). Microbial traces and their role in forensic science. Journal of Applied Microbiology, **132(4)**, 2547-2557.
21. Sugita, R., & Marumo, Y. (1996). Validity of color examination for forensic soil identification. **Forensic Science International**, **83(3)**, 201-210. https://doi.org/10.1016/S0379-0738(96)02038-5.

22. Sugita, R., & Marumo, Y. (2001). Screening of soil evidence by a combination of simple techniques: Validity of particle size distribution. **Forensic Science International**, **122(2–3)**, 155-158. https://doi.org/10.1016/S0379-0738(01)00490-X.
23. Woods, B., Kirkbride, K.P., Lennard, C., & Robertson, J. (2014). Soil examination for a forensic trace evidence laboratory – Part 2: Elemental analysis. **Forensic Science International**, **245**, 195-201. https://doi.org/10.1016/j.forsciint.2014.10.018.
24. Young, J. M., Rawlence, N. J., Weyrich, L. S., & Cooper, A. (2014). Limitations and recommendations for successful DNA extraction from forensic soil samples: a review. Science & Justice, **54(3)**, 238-244.
25. Young, J. M., Higgins, D., & Austin, J. J. (2021). Soil DNA: advances in DNA technology offer a powerful new tool for forensic science.
26. **https://www.fbi.gov/news/stories/-serial-killers-part-5-wayne-williams-and-the-atlanta-child-murders**
27. **https://www.fbi.gov/history/famous-cases/lindbergh-kidnapping**
28. **https://www.bbc.com/news/av/uk-34972009**.