Microbial Forensics

My microbiome is unlike anyone else's,
and there is evidence to prove it.

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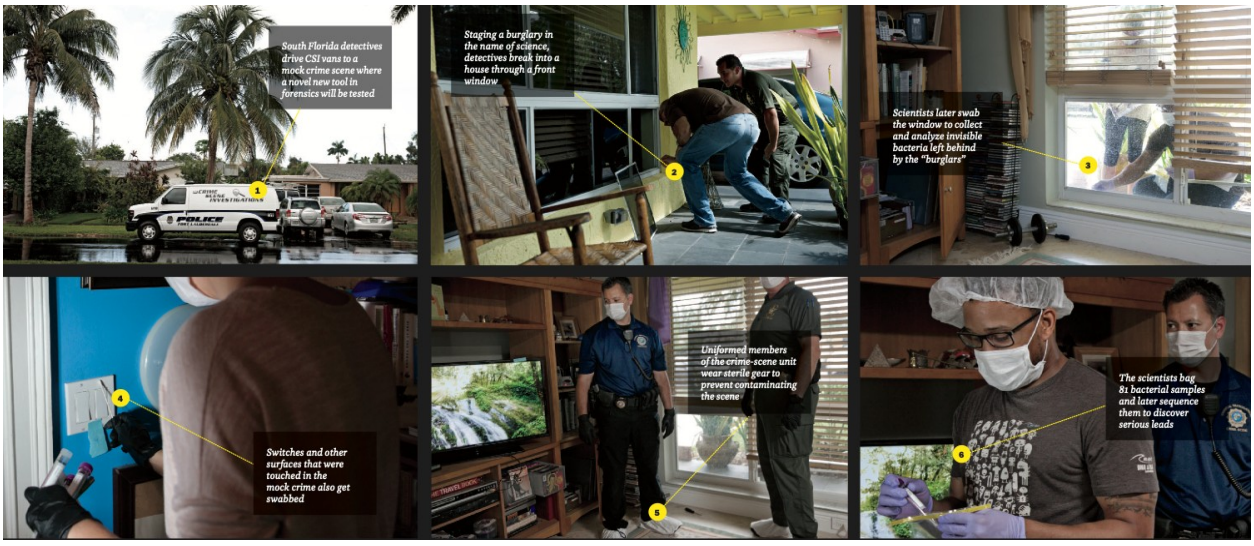
Storyline

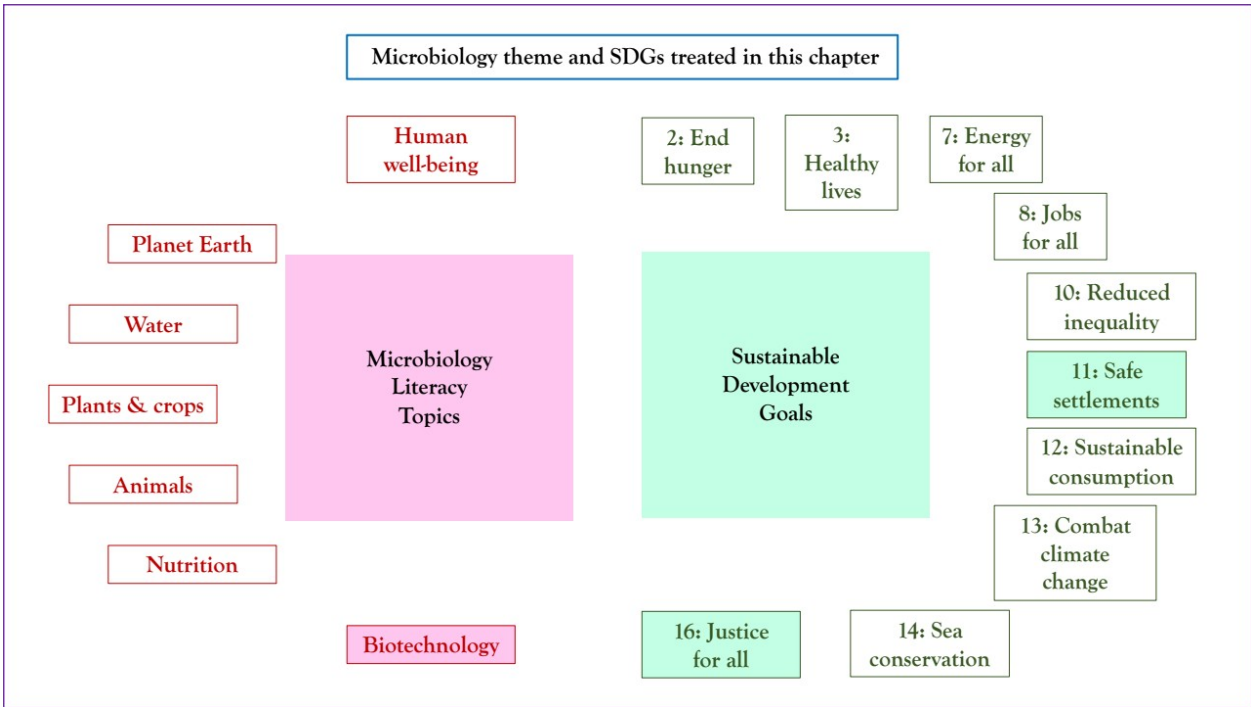
A critical component to any forensic investigation is the recovery and identification of evidence at a crime scene, which aids investigators in solving the crime. This can range from witnesses at the crime scene to fingerprints and/or DNA recovered from an object. In addition to those above, another common type of evidence is trace evidence, which is macroscopic to microscopic objects left behind via contact between the suspect and the crime scene. For example, dirt from the suspect's shoe can give investigators a clue to where the individual commonly resides or works, and fibers from the suspect's clothing can be used to match fibers found on the victim, providing circumstantial evidence that he/she was potentially present at the scene of the crime. Recently, investigators have begun to explore whether our microbiome can be used to identify people and the places they have been. Humans contain as many microbial cells as their human cells, and we constantly shed millions of microbes into our immediate environments. This makes microbes an intriguing biological signal to track and profile, which is similar to how investigators use fingerprints and DNA to identify people. Thus, the study of human microbiomes may serve as the next tool in forensics, given its potential to identify any given person among a population.



The picture above demonstrates the recommended steps to collect microbial evidence at a crime scene, which mirror the procedures already established by crime scene investigators. Because microbiomes can be found anywhere, collected evidence used to check for DNA could also be used to detect the microbial taxa present.

The Microbiology and Societal Context

The microbiology: microbiome analysis; time-dependent changes in crime scene microbiota. *Sustainability issues:* safe cities and human settlements; peaceful and inclusive societies, and justice for all



Microbial Forensics: the Microbiology

1. ***What are microbiomes?*** A microbiome is the collection of microorganisms (bacteria, archaea, fungi, etc.) found within an environment. Microbiomes can be found in and on everything, including humans, animals, plants, soil, buildings, and even air. More importantly, each environment's microbiome is unique from others: a microbiome of a plant will look entirely different from the microbiome of someone's home. We humans, for example, contain over 10 trillion microorganisms, which collectively weigh nearly as much as the human brain. Human microbiomes play essential roles in aiding digestion, impacting behavior, and protecting from disease-causing bacteria, among many other functions. Ultimately, our microbiomes play an important role in shaping our health and serving as traceable markers about lifestyle and the environments in which we reside.

2. ***What is forensics?*** Forensics is the scientific method to solving crimes, which started in the late 18th century. Forensics focuses on crime-relevant objects or substances that are analysed by methodologies of different scientific disciplines, such as chemistry, biology, and physics. For example, DNA may be collected from a crime scene in order to identify potential subjects. On the other hand, chemistry may be applied to label an unidentified material and/or liquid discovered. Law enforcement agents rely on scientists to provide them clues that help reconstruct the events of the crime. More importantly, forensics also helps absolve individuals who are innocent. This is why the process by which investigators collect evidence, how that evidence is handled and transported to the lab, and the methods used to come to a conclusion, are all important aspects and require attention to detail by everyone involved.

3. ***Detecting clues at a crime scene.*** One of the most significant advancements in forensics has been the introduction and development of *trace evidence*. Trace evidence is commonly employed to reconstruct crime scenes, as well as the people and things involved. This can range from tiny fragments of physical evidence, such as hair fibers and/or pieces of glass, to human tissue/remains left at the scene. While trace evidence often takes a back seat to DNA evidence, it has become a critical tool for forensic investigations and provides clues about the events that took place. More recently, forensic investigators have begun to explore whether they can use a person's microbiome as a forensic tool. Given that human microbiomes are relatively unique to the individual and are shed in the spaces an individual resides, the human microbiome is somewhat similar to DNA profiling, which has been used for decades.

Microbial taxa could be used to identify people. Because each person's microbiome is unique, it is believed that each person carries a set of microbial taxa that is only found on them. Investigators can take advantage of this uniqueness to match suspects to microbial taxa collected at a crime scene.

4. ***Humans harbor microbes that identify their host.*** Humans carry a highly individual microbial combination that is as unique as a human fingerprint. More importantly, humans shed roughly 36 million microbial cells each hour into the environment they currently reside, mostly from their exposed skin. Scientists have demonstrated that individuals can be identified based solely on their microbes. Also, the objects we touch consistently reflect the microbiomes found on our skin and in our gastrointestinal tract. Individuals have been routinely identified based on their bathrooms, cell phones, doorknobs, floors, and many other surfaces within our homes, workplaces, and hospitals. The ability to match individuals to their environment solely on the basis of their microbiome is intriguing to investigators. For instance, this makes it possible to link suspects to burglaries by connecting the suspect to physical evidence via their microbiome.

5. ***Microbiomes are location tags.*** Initiatives such as the *Earth Microbiome Project* (EMP) and *American Gut Project* (AGP) have demonstrated that microbial communities are distinctly different across geographical locations. The EMP and AGP are among the two largest citizen-driven science projects to date with more than 100,000 samples provided by individuals interested in understanding their health or the world around them. From these efforts, scientists have been able to identify microbes around the world, as well as the people who inhabit these environments. We now have a better understanding regarding how diet affect us, how changes in pH affect aquatic life, and how microbes establish themselves in built-environments such as homes and hospitals. The soil, plants, and even the air found within different environments serve as traceable microbial signatures. Recently, this has been applied to urban environments such as cities where offices in New York versus offices in Chicago are distinctly different in their microbial makeup. This makes it possible to place suspects at a scene of a crime if they visited a city.

6. ***Microbiomes after death.*** Even after death, the microbiome can still provide clues to investigators. Microbes are often a reliable indicator of how long an individual has been dead. This is because post-mortem a person's microbiota changes in a particular pattern over time, changes that take place slower or faster, depending on how cold or hot it is, which creates a "microbial death clock." More importantly, the microbiome can serve as an indicator of the manner by which someone has died, allowing investigators to potentially determine whether the crime scene matches where a person died and whether it was of natural causes or not.

Researchers are currently working on smart environments, where sensors that can track microbial taxa are built into existing architecture found within cities such as lamp posts, buildings, and public transit among many others. The goal is to allow active monitoring of built-environments and to detect unfavorable changes and/or threats instantly. This would help to shorten response times and possibly prevent outbreaks.

7. ***Developing microbial trackers.*** Researchers, investigators, and companies have begun to develop new technologies to address the challenges of incorporating the microbiome in forensics, ranging from monitoring devices to databases allowing dwellings to collect information. One recent development has been the use of microbial air sensors, which are devices that analyze aerosolized microbes. While this is important for understanding how disease and microorganisms are spread, it could also identify microbial communities foreign to its environment, i.e., identifying an intruder in a home, based on the microbes they emit. Furthermore, microbial sensors have been placed in toilets to track a person's health, water systems to track the spread of pathogens, and cities to monitor potential outbreaks. However, it will take time to develop these tools to be reliable, accurate, and effective for law enforcement and researchers alike.

8. Goals for future developments

Goal 1: Identifying microbial taxa that consistently differ between people. What makes the microbiome unique are the multitude and diversity of microbes that exist in humans. In theory, no two humans will have the same microbial combinations. However, many of the microbes humans harbor can shift their abundance in response to environmental changes. It is pertinent to identify microbial taxa universally found in all humans but are unique in structure or genome among individuals. This would make adopting the microbiome easier as it would resemble DNA profiling using short tandem repeats, which is considered the gold standard in forensics.

Goal 2: Develop a database of human microbiomes. Human microbiomes have been widely studied, and researchers have conducted numerous studies connecting human microbes to an individual's lifestyle, as well as where they live. Unlike DNA profiling, housed under a single, unified database (CODIS), human microbiome data is scattered and disparate. In order to fully incorporate the microbiome as a forensic tool, they are developing a database that researchers and law enforcement can collectively access to improve the standards and guidelines that are accepted and approved for forensic investigations.

Goal 3: Improve accuracy and reliability of detection. Currently, the human microbiome lacks the accuracy (less than 90%) that is deemed acceptable within forensics compared to other standard techniques, i.e., DNA profiling is approximately 99% accurate. Additionally, this is very much associated with the population of microbiomes being analyzed. As the number of collected and analyzed microbiomes increase, researchers and law enforcement must draw the same conclusions time and time again.

Goal 4: Utilize the microbiome to aid forensic investigations. One of the major difficulties in any unsolved crime is reconstructing the events and timelines of a crime scene. Crime scene investigators will often use an array of tools at their disposal, all of which have some drawbacks. Implementing the microbiome as trace evidence may assist investigators by providing circumstantial evidence, with such "leads" potentially reducing investigation times, connecting forensic tools, clarifying timelines of past events, and eliminating potential suspects. In order to better understand the microbiome's potential in forensics, it must become regularly integrated in forensic investigations.

Goal 5: Advancing microbial research. Microbiome research is still in its infancy in comparison to other fields of research, and there is still a lot we do not know. As the body of knowledge grows and technology continues to improve, the human microbiome and its influence will become more apparent. In the meantime, it is important to continue to push the boundaries of the utility of the microbiome.

Relevance for Sustainable Development Goals and Grand Challenges

- **Goal 11. Make cities and human settlements inclusive, safe, resilient and sustainable.** Effective crime solving is central to discouraging crime and hence key to creating and maintaining safe and inclusive settlements. Microbiome-based forensics has the potential not only to track people throughout the spaces they occupy but aspects regarding their habits and lifestyle, which indirectly contribute to solving and hence crime discouragement.
- **Goal 16. Promote peaceful and inclusive societies for sustainable development, provide access to justice for all and build effective, accountable and inclusive institutions at all levels.** The ability of law enforcement agencies to obtain rigorous evidence unambiguously linking perpetrators to crimes lies at the heart of law enforcement and justice. Microbiome-based forensics has exceptional potential to contribute to crime solving and hence the advancement of fair and effective justice systems.

Potential Implications for Decisions

1. ***Individual***
    a. Participating in citizen science research
        i. Learn about your own microbiome
        ii. Help build knowledge that will inform future experiments and policy
    b. Attending scientific talks
        i. Creates opportunity to talk directly to scientists
        ii. Encourages scientists to be transparent about their findings

2. ***Community policies***
    a. Advocating for policies that include the microbiome
        i. Enhances transparency between scientists and public
        ii. Informs local officials of public needs and wants
    b. Becoming earlier adopters of new technology
        i. Replaces outdated technology and practices
        ii. Aids in developing informed systems

3. ***National policies***
    a. Developing a microbiome database
        i. Creates a data center for all people to access
        ii. Serves as a benchmark for tools and technology to be used for forensics
    b. Establishing microbiome standards for forensics
        i. Promotes reproducible tests and reduces bias
        ii. Guides the workforce in identifying strengths and weaknesses, allowing for improvements

Pupil Participation

1. ***Class discussion about forensics and crime***
    a. Where can crimes happen?
    b. What tools can investigators use to find clues at a crime scene?

c. How can microbiomes be helpful for investigators?

2. Class discussion on human microbiome

a. What do you currently know about the microbiome?
b. What is your normal routine, and how could that affect your microbiome?
c. What could suddenly change your microbiome?

3. ***Mock burglary exercise***

Let's have some fun! As a class, think of a possible burglary. Identify one person in the classroom to act as the suspect and the rest of the classmates will be detectives. The detectives must use what they know about microbes to identify all the mistakes the suspect made.

a. What were the detectives able to find out about the burglary?
b. How can the microbiomes be used to prove the suspect committed the crime?

4. Pupil stakeholder awareness

a. Microbes can be beneficial to law enforcement to solve crimes. List three ways microbes can be used to provide evidence?
b. Microbiomes play an important role in shaping our health and serving as traceable markers about our lifestyle. Can you think of three ways in which microbes could identify a person's everyday lifestyle routine?
c. Create a scenario requiring the use of microbes to solve a problem?

The Evidence Base, Further Reading and Teaching Aids

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Glossary

Trace evidence: physical materials and objects that transfer from one source to another and are collected by law officials – usually at a crime scene – during an investigation.
Macroscopic: visible by the naked eye and not requiring a microscope
Microscopic: so small that a microscope is needed to view
Circumstantial: pointing indirectly to something but not a direct link
Commensal: Establishing a close relationship to a host generally without negative consequences
Microbiome: the collection of microorganisms in a given environment, including a person's body or part of their body
Absolve: To be free of blame or guilt
Urban environment: a place or area with a dense population often referring to the number of people in the area
Post-mortem: an examination of a dead body to determine the cause of death
Workforce: people engaged in activity who generally work for the same company or area