Modeling Bacterial Growth and Control Using Cellular Automata: A Python-Based Approach

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Abstract

Bacterial growth and its control are fundamental topics in epidemiology, microbiology, and computational modeling. In this study, we implement a **cellular automaton (CA) model in Python** to simulate the propagation and control of bacterial colonies under various environmental conditions. This model enables researchers to visualize bacterial spread, mortality due to antibiotics, the emergence of resistant strains, and the impact of resource limitations and barriers. By adjusting key parameters, we demonstrate how bacterial populations react to different interventions, contributing to a better understanding of antibiotic resistance and infection control strategies.

Introduction

Bacterial infections present a significant challenge in medical and environmental sciences, particularly with the increasing **resistance to antibiotics**. Computational models provide a robust way to simulate bacterial growth and study interventions such as antibiotics and physical containment measures. **Cellular automata (CA)** offer an intuitive framework for modeling bacterial colonies, where each cell represents a discrete spatial unit evolving over time according to predefined rules. This study presents a **Python-based cellular automaton model** designed to explore bacterial growth dynamics, resistance development, and the effects of environmental constraints.

Methods

Cellular Automata Model for Bacterial Growth

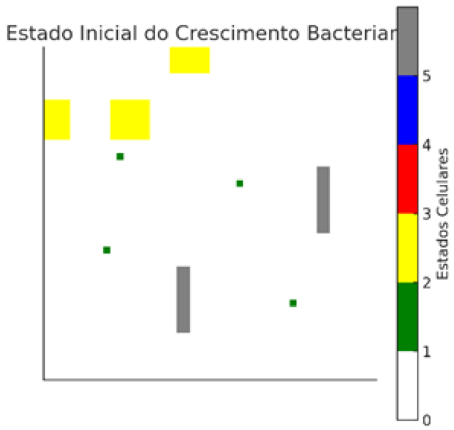
The bacterial growth model is constructed using a **50×50 grid**, where each cell represents a discrete location in the bacterial environment. Each cell can exist in one of six states:

- **EMPTY (White):** No bacteria present.
- **BACTERIA (Green):** Active bacterial colony that can grow and spread.
- **LIMITED RESOURCES (Yellow):** Regions where bacterial growth is slower due to nutrient scarcity.
- **DEAD (Red):** Bacteria eliminated by antibiotics or resource depletion.
- **RESISTANT (Blue):** Bacteria that have developed antibiotic resistance.
- **BARRIER (Gray):** Areas where bacteria cannot grow due to physical or chemical restrictions.

Dynamics and Model Transitions

Each iteration represents a **single time step** in bacterial evolution, following these rules:

- **Bacterial Growth:** Bacteria spread to adjacent empty cells with a probability defined by `GROWTH_PROB`.



Source: own authorship. Available at: https://github.com/AndrePereira768/Epidemiologia2025

- **Limited Resources:** If a new bacterial cell lands in a resource-limited area, its probability of growth decreases (`LIMITED_GROWTH_PROB`).

- **Antibiotic Application:** Non-resistant bacteria have a probability (`ANTIBIOTIC_EFFECTIVENESS`) of being eliminated when exposed to antibiotics.
- **Resistance Development:** A fraction (`IMMUNITY_RATE`) of bacteria can mutate and become antibiotic-resistant (blue) instead of dying.
- **Resistance Lifetime:** Resistant bacteria have a finite lifespan (`RESISTANCE_LIFETIME`), after which they die.
- **Reinfection:** Dead bacteria can occasionally be replaced by new bacterial colonies (`REINFECTION_RATE`).
- **Barrier Effects:** Bacteria cannot cross gray areas, simulating physical barriers such as immune responses or antibiotic walls.

Python Implementation

The simulation is implemented in **Python** using:

- **NumPy:** Efficient manipulation of the 50×50 grid.
- **Matplotlib:** Real-time visualization of bacterial propagation.
- **Matplotlib.colors:** Custom colormaps to differentiate bacterial states.
- **Animation functions:** To create a dynamic visualization of bacterial behavior over multiple iterations.

A key feature of the model is its adaptability—users can **adjust parameters** (e.g., antibiotic effectiveness, resistance probability, reinfection rate) to explore different epidemiological scenarios.

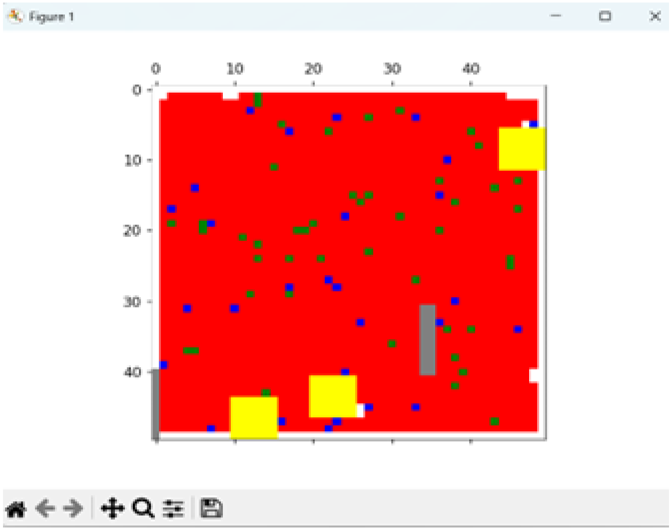
Results and Discussion

Observing Bacterial Growth Patterns

Initially, bacterial colonies (green) expand to occupy available space. If barriers (gray) or resource-limited areas (yellow) are present, growth is reduced or restricted.

Impact of Antibiotics

As iterations progress, antibiotics begin eliminating susceptible bacteria (red regions appear). If `ANTIBIOTIC_EFFECTIVENESS` is high, bacterial mortality increases rapidly, leading to colony collapse. However, if resistance mutations occur (`IMMUNITY_RATE`), blue bacteria persist, simulating the **real-world challenge of antibiotic resistance**.



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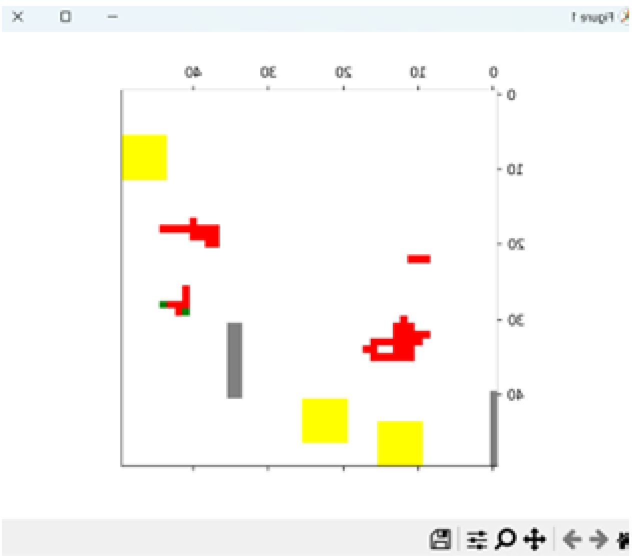
The Role of Barriers and Limited Resources

Barriers (gray) significantly affect bacterial propagation, restricting movement and **mimicking immune system responses** or **physical antibiotic applications**. Resource-limited regions (yellow) reduce growth rates but do not completely prevent bacterial survival, similar to environments with low nutrient availability.



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Conclusion

This Python-based cellular automaton model successfully simulates bacterial growth, resistance development, and antibiotic interventions. The model highlights key epidemiological concepts such as **infection spread, antibiotic resistance emergence, and containment strategies**. By adjusting parameters, researchers can explore different infection control methods, making the model a valuable tool for epidemiology, public health, and microbiology education. Future improvements may include **stochastic environmental variations**, **host immune responses**, and **simulations of multidrug resistance**. By refining this model, we can better predict bacterial behavior and inform effective infection treatment strategies.

References

- Schiff, J. L. (2008). *Cellular Automata: A Discrete View of the World*. Wiley.
- Wolfram, S. (2002). *A New Kind of Science*. Wolfram Media.
- Murray, J. D. (2002). *Mathematical Biology*. Springer.
- Nowak, M. A., & May, R. M. (2000). *Virus Dynamics: Mathematical Principles of Immunology and Virology*. Oxford University Press.