



A Mathematical Approach to Ecological Modeling with Antibiotic Effects on Bacterial population in the Human Body: A Python Implementation

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ABSTRACT

The paper analyzes Ecological Amensalism through mathematical modeling that reproduces bacterial population growth dynamics and antibiotic growth dynamics. The antibiotics prevent bacterial growth but do not influence the human body during this interaction. A set of differential equations represents the bacterial and antibiotic dynamical process which reveals a two-species relationship where one species obtains a negative impact without any effects on the other species. Numerical calculations reveal how modifications of antibiotic effectiveness and decay mechanisms affect bacterial reduction results.

1. INTRODUCTION

The ecological pattern of amensalism consists of harmful effects on one organism without impacts on the second organism. Ecological interactions which produce amensalism appear naturally in ecosystems through two mechanisms including resource competition and allelopathic chemical releases. The research merges amensalism with bacterial-antibiotic interactions in human bodies through mathematical models to analyze population dynamics using numerical simulations. This study analyzes the antibiotic effects on bacterial population growth through quantitative assessments of different controlling factors.

The biological relationship known as amensalism demonstrates two effects since one participant suffers damage but the other does not experience any change. Such one-way interaction stands distinct from mutualism and commensalism as well as parasitism and competition. Amensalism functions through single-sided negative influence which stops one organism yet leaves the other organism without any effects. The relationship between species leaves the unaffected one unchanged since it neither benefits nor suffers from the interaction. The natural ecosystem displays frequent amensalistic relationships because multiple organisms fight over scarce resources or discharge restraining substances that reduce the growth of other organisms.

Microbial production of penicillin represents amensalistic behavior since *Penicillium* fungi create penicillin that stops bacterial growth but has no effect on the fungus. Large trees in forest ecosystems act as sun blockers which prevents understory plants from growing beneath them yet leave the large trees unaffected by this blockage. Through allelopathy the black walnut plant (*Juglans nigra*) emits soil chemicals that prevent surrounding plant species from growing properly.

Ecosystem structure together with population regulation and species diversity strongly depend on this form of organismal interaction. Evidence-based ecological modeling utilizes amensalism relationships to depict how human bodies function as hosts with antibiotics acting upon bacteria populations. The antibiotics directly affect bacteria populations but leave the host untouched. The relationship between antibiotic treatment and bacterial suppression can be modeled mathematically using differential equations for conducting simulations about ecological amensalism dynamics.

1.1 Notations

$B(t)$: Population of bacteria at time t .

$A(t)$: Concentration of antibiotics at time t .

Human body states at time t remain unaffected by the interaction which is noted as $H(t)$.

1.2 Assumptions:

The substance antibacterial specifically restricts bacterial growth patterns.



This interaction does not cause any effects on the human body when antibiotics sustain directly inside it. Bacteria populations grow according to logistic growth patterns if antibiotics do not influence their development process.

(iv).Antibiotics decay naturally over time.

2. MATHEMATICAL EQUATIONS

Differential equations describe the mathematical relationship between bacteria and antibiotics through the following system of equations:

1. Logistic Growth Model with Antibiotic Effect

This interaction becomes the following mathematical system:

$$(1). \frac{dB}{dt} = r_B B \left(1 - \frac{B}{K_B} \right) - \alpha AB$$

$$(2). \frac{dA}{dt} = -d_A A$$

$$(3). \frac{dH}{dt} = 0$$

Where:

r_B : Intrinsic growth rate of bacteria.

K_B : Carrying capacity of the bacterial population.

α : Antibiotic efficacy constant (rate at which antibiotics inhibit bacterial growth).

d_A : Natural decay rate of antibiotics.

$A(t)$: Antibiotic concentration over time.

$H(t)=\text{constant}$: Human body remains unaffected.

2.1 Explanation of the Equations

$\frac{dB}{dt}$
Bacterial Growth ($\frac{dB}{dt}$) :

Bacteria grow logistically ($r_B B \left(1 - \frac{B}{K_B} \right)$)

Bacterial growth reduction depends on the concentration of antibiotics and the bacterial population rate through the factor αAB .

$\frac{dA}{dt}$
Antibiotic Decay ($\frac{dA}{dt}$) :

Antibiotics degrade over time at a rate proportional to $d_A A$.

$\frac{dH}{dt}$
Human Body ($\frac{dH}{dt}$) :

The state of the human body is constant because it is not directly affected by this interaction.

3. METHODOLOGY AND NUMERICAL SIMULATION

A mathematical model together with numeric simulations through Python was used to examine bacterial population interactions with antibiotics inside an amensalistic relationship. A numerical solution of the bacterial



and antibiotic population model was achieved through the implementation of Euler's method which provides an easy approach to approximate solutions of ordinary differential equations. This model includes two interconnected ODEs that depict the bacterial population growth along with antibiotic substance reduction based on genuine biological parameters.

A modified logistic growth equation addresses the antibiotic inhibition on the bacterial population $B(t)$ through:

$$\frac{dB}{dt} = r_B B \left(1 - \frac{B}{K_B} \right) - \alpha AB$$

The model recognizes antibiotic concentration $A(t)$ through an exponential decay function.

$$\frac{dA}{dt} = -d_A A$$

3.1 Parameters and Assumptions

The mathematical model relies on three important assumptions which support both biological accuracy together with design simplicity.

- (i). The antibiotic drugs pause bacterial replication but they do not impact human cells which displays amensalistic relationships.
- (ii). The growth pattern of bacteria follows logistic patterns under antibiotic-free conditions yet remains limited to the carrying capacity K_B .
- (iii). The decaying process of antibiotics occurs naturally without needing bacterial growth or host biological components.

4. NUMERICAL SIMULATION

An analysis of this system requires defining the following conditions, along with specified parameters:

- Initial bacterial population: $B(0)=100$
- Initial antibiotic concentration: $A(0)=10$
- Bacterial growth rate: $r=0.1$
- Carrying capacity: $K_B=1000$
- Antibiotic efficacy: $\alpha=0.05$
- Antibiotic decay rate: $d_A=0.02$
- Time step for Euler's method: $h=0.1$
- Total simulation time: e.g., 100 units (e.g., hours or days)

A simulation uses these equations to determine fresh values of B and A during each time step. The Euler update rules are:

$$B_{n+1} = B_n + h \left[r B_n \left(1 - \frac{B_n}{K_B} \right) - \alpha A_n B_n \right]$$

$$A_{n+1} = A_n + h (-d_A A_n)$$

4.1 Euler's Update Formulas (Discrete Time Step Integration)

At each iteration step iii , the values are updated as:

$$B_i = B_{i-1} + \Delta t \cdot \left[r_B \cdot B_{i-1} \left(1 - \frac{B_{i-1}}{K_B} \right) - \alpha \cdot A_{i-1} \cdot B_{i-1} \right]$$

$$A_i = A_{i-1} + \Delta t \cdot [-d_A \cdot A_{i-1}]$$

These time-dependent formulas enable approximate calculation of $B(t)$ and $A(t)$ solutions by repeating their operations. The quick computational performance of Euler's method reaches its best accuracy when applying small time intervals in stable systems.



5. RESULTS FROM THE SIMULATION

The antibiotic reduces bacterial numbers throughout time through its inhibitory properties on bacteria.

The antibiotic concentration continuously lowers during the time period which eventually leads to elimination of bacterial system susceptibility.

Amensalism occurs through the model when the human body remains unchanged by both bacterial populations in this system.

The model tracks how medications impact microbial growth dynamics while it proves that selecting precise medication values for efficacy and breakdown supports better therapeutic outcomes. The obtained methodology allows researchers to create further versions of the model that include defense responses from immune systems and microbial protective approaches.

5.1 Python Program:

```
import numpy as np
import matplotlib.pyplot as plt
# Parameters
r_B = 0.1 # Growth rate of bacteria
K_B = 1000 # Carrying capacity of bacteria
alpha = 0.05 # Antibiotic efficacy constant
d_A = 0.02 # Antibiotic decay rate
# Initial conditions
B0 = 100 # Initial bacteria population
A0 = 10 # Initial antibiotic concentration
H0 = 1 # Human body state (assumed constant)
# Simulation time settings
t_max = 100 # Maximum time for simulation
dt = 0.1 # Time step
time = np.arange(0, t_max, dt)
# Initialize arrays for populations and concentrations
B = np.zeros_like(time)
A = np.zeros_like(time)
H = np.ones_like(time) * H0
# Set initial values
B[0] = B0
A[0] = A0
# Numerical integration (Euler's method)
for i in range(1, len(time)):
    dB = r_B * B[i-1] * (1 - B[i-1] / K_B) - alpha * A[i-1] * B[i-1]
    dA = -d_A * A[i-1]
    B[i] = B[i-1] + dB * dt
    A[i] = A[i-1] + dA * dt
# Plotting the results
plt.figure(figsize=(12, 6))
# Plot bacterial population
plt.plot(time, B, label="Bacteria Population (B)", linewidth=2)
# Plot antibiotic concentration
plt.plot(time, A, label="Antibiotic Concentration (A)", linewidth=2, linestyle="--")
# Plot human body state (constant line)
plt.axhline(y=H0, color='green', linestyle=':', label="Human Body State (H)")
# Plot settings
plt.title("Amensalism Interaction: Bacteria and Antibiotics", fontsize=14)
plt.xlabel("Time", fontsize=12)
plt.ylabel("Population / Concentration", fontsize=12)
```

```
plt.legend()
plt.grid(True)
# Show plot
plt.show()
```

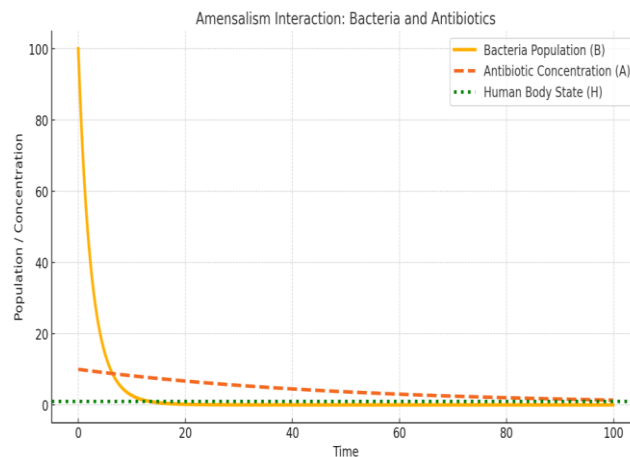


Figure (1): Amensalism Integration: Bacteria Vs Antibiotics

This graph demonstrates how human body state maintains its constant state while bacteria encounter antibiotic treatment over time.

The bacterial population (B) descends in numbers due to antibiotic inhibition mechanisms.

The antibiotic concentration in the solution shows natural decay during the time period.

The human body state maintains a constant state since it experiences no effects during this interaction period. Different cases require the modification of essential parameters (bacterial growth rate, antibiotic efficacy and decay rate) to visualize their impact on this interaction. The next section contains three distinctive scenarios which demonstrate their comparative effects.

5.3 Scenarios

1. **Baseline Case:** Default parameters.
2. **High Antibiotic Efficacy:** Increased antibiotic efficacy (α).
3. **Fast Antibiotic Decay:** Increased antibiotic decay rate (d_A).

Python Program:

```
import numpy as np
import matplotlib.pyplot as plt
# Define scenarios
scenarios = [
    {"label": "Baseline Case", "r_B": 0.1, "alpha": 0.05, "d_A": 0.02},
    {"label": "High Antibiotic Efficacy", "r_B": 0.1, "alpha": 0.1, "d_A": 0.02},
    {"label": "Fast Antibiotic Decay", "r_B": 0.1, "alpha": 0.05, "d_A": 0.05},
]
# Initialize figure
plt.figure(figsize=(15, 10))
# Time settings
t_max = 100
dt = 0.1
time = np.arange(0, t_max, dt)
# Initial conditions
B0 = 100 # Initial bacteria population
A0 = 10 # Initial antibiotic concentration
K_B = 1000 # Carrying capacity of bacteria
```

```
# Loop through scenarios
for scenario in scenarios:
    # Extract parameters
    r_B = scenario["r_B"]
    alpha = scenario["alpha"]
    d_A = scenario["d_A"]
    label = scenario["label"]
    # Reset initial conditions
    B = np.zeros_like(time)
    A = np.zeros_like(time)
    B[0] = B0
    A[0] = A0
    # Numerical integration (Euler's method)
    for i in range(1, len(time)):
        dB = r_B * B[i-1] * (1 - B[i-1] / K_B) - alpha * A[i-1] * B[i-1]
        dA = -d_A * A[i-1]
        B[i] = B[i-1] + dB * dt
        A[i] = A[i-1] + dA * dt
    # Plot bacterial population with increased thickness
    plt.plot(time, B, label=f"{label} - Bacteria (B)", linewidth=3)
    # Plot antibiotic concentration with increased thickness
    plt.plot(time, A, label=f"{label} - Antibiotics (A)", linestyle="--", linewidth=3)
# Plot settings
plt.title("Comparative Analysis of Bacteria and Antibiotics under Different Scenarios", fontsize=14)
plt.xlabel("Time", fontsize=12)
plt.ylabel("Population / Concentration", fontsize=12)
plt.legend(fontsize=10, loc="upper right")
plt.grid(True)
plt.show()
```

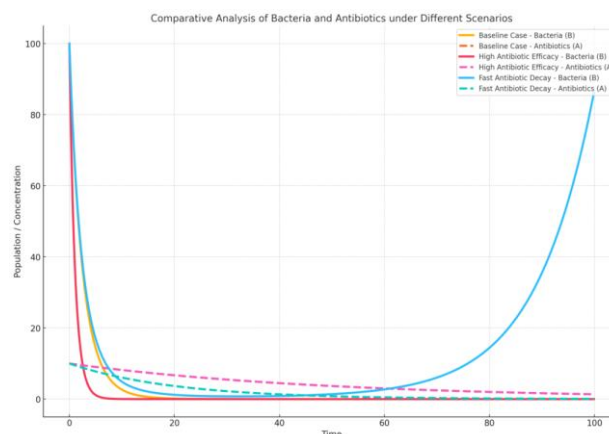


Figure (2): Comparative Analysis of Bacteria and Antibiotics

The analysis shows how bacteria relate to antibiotics when the environment includes three different circumstances.

- (i). Regular bacteria spread meets an average response of antibiotics with normal rate of decay at the baseline.
- (ii). The effectiveness of antibiotics is very high because this produces quick reductions of bacterial numbers in the population.
- (iii). The speed of antibiotic degradation becomes faster in a way that reduces the influence of antibiotics on bacterial populations.



6. Conclusion for the Comparative Analysis

The analysis examines how bacterial populations respond to antibiotic concentrations through three specified conditions to study varying effects of antibiotic effectiveness (α) and antibiotic decay rate (d_A). Here are the detailed insights:

6.1 Baseline Case (Moderate Efficacy and Decay Rate)

A normal and effective antibiotic treatment scenario emerges from the baseline case which combines moderate antibiotic efficacy with decay rate. During the early phase the bacterial numbers expand before antibiotic intervention produces swift decline of the population. Therefore the antibiotic concentration decreases gradually until the system reaches stability. Natural bacterial control demonstrates equilibrium through antibiotic antiviral properties which successfully restrain bacterial reproduction followed by a reduction of antibiotic presence when the infection is controlled.

6.2 High Antibiotic Efficacy (Increased α)

The rapid decrease of bacteria occurs under high antibiotic conditions that outpaces baseline levels even though antibiotic amounts fade away at identical rates. Fast bacterial growth suppression signals how effective powerful antibiotics can decrease bacterial survival periods. The quick reduction of bacteria due to strong antibiotics poses a danger because improper dosing or incomplete medication completion may lead to antibiotic-resistant bacterial strains. The swift accomplishment of treatment aims can be accomplished through high efficacy but careful administration is needed to prevent long-term negative effects.

The present scenario shows efficiency in treating vital bacterial infections by providing immediate bacterial control which medical professionals need. Rapid bacterial control achieved through this antibiotic medication becomes critical for saving lives in dangerous infection situations. The management of resistance risks requires appropriate antibiotic dosing together with proper treatment duration to ensure long-term treatment success.

6.3 Fast Antibiotic Decay (Increased d_A)

The rapid decline of antibiotic concentration in this example demonstrates the difficulties linked to antibiotic decay which happens faster than normal cases. The bacterial population displays weakened ability to decline because antibiotic levels diminish rapidly resulting in survivor bacteria that might regain presence after initial treatment effects. The outcome proves that having consistent antibiotic levels across the bloodstream ensures bacterial complete elimination. Fast bacterial drug breakdown requires patients to take greater antibiotic amounts or undergo regular administration procedures in order to sustain treatment outcomes and limit secondary bacterial growth.

The analysis produces important widespread knowledge about the breakdown of antibiotic effectiveness when combined with bacterial population responses. roteinological characteristics which lead to efficient bacterial suppression become essential for developing individualized treatment strategies because they affect the dosage determination through minimum inhibitory concentration (MIC) assessments. A fast antibiotic decay rate shortens the treatment duration so bacteria can escape elimination which prompts healthcare providers to explore sustained-release drugs or longer-acting agents.

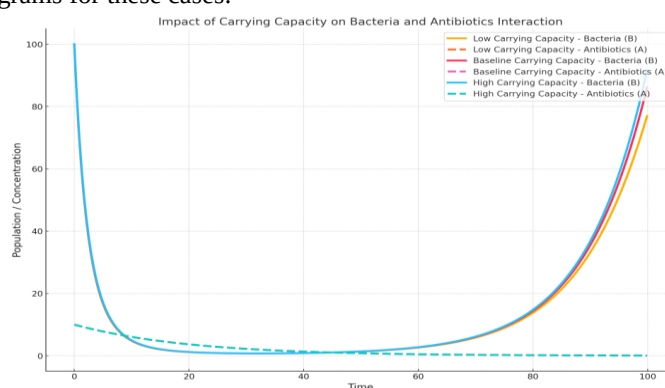
The rapid decay of antibiotics creates a risk of bacteria survival which emphasizes the importance of designing medication schedules that patients follow correctly to prevent therapeutic failure. Even though this model does not explicitly represent human bodies in practice immune responses together with medication side effects heavily affect the results of treatment.

The broadened implications reach healthcare as medical providers need to customize antibiotic treatment plans between maximizing treatment outcomes and preventing drug-resistant bacteria emergence. Scientists who use this model augment its application with mechanisms of drug resistance along with immune system responses and combination therapeutic approaches to achieve advanced knowledge. The responsible combat against antibiotic resistance depends heavily on public education efforts which help prevent misuse of antibiotics. Research into the link between bacterial carrying capacity (K_B) will enhance our comprehension of population restrictions during antibiotic treatments to develop better therapeutic measures.

7. Impact of Bacterial Carrying Capacity (K_B) on Antibiotic-Bacteria Dynamics

A simulation was designed to study the bacterial carrying capacity effect on bacterial population (B) and antibiotic concentration (A) interactions by testing three distinct values of K_B : low ($K_B = 500$) along with baseline ($K_B = 1000$) and high ($K_B = 2000$). The simulations ran alone separately to determine how K_B modifies the system dynamics between bacterial components and antibiotic rules. The individual plots enable us to examine bacterial growth patterns as well as antibiotic suppression effectiveness and stabilization times among other prototypical behaviors. The methodology generates better insights about how environmental factors and biological conditions expressed through K_B impact the course of therapy and aid the development of improved therapeutic treatments.

The simulations and diagrams for these cases:



Figure(3): Impact of Carrying Capacity on Bacteria and Antibiotics Interaction

The presented graph shows how changes in carrying capacity (K_B) affect the bacterial population (B) and antibiotic concentration (A) relationship:

7.1 Observations

Numerical simulation shows specific behavior patterns which show how antibiotic treatment emerges from bacterial population control (K_B) fluctuations.

The bacterial population in the low carrying capacity environment ($K_B = 500$) achieves lower maximum value before antibiotics eliminate it. Because there are lesser bacterial cells the antibiotic substances have a shorter time to act on them.

When carrying capacity sets at 1000, the bacterial numbers reach greater heights which leads to antibiotic activity lasting longer because the drug blocks a larger number of cells.

Under the high carrying capacity environment with K_B set to 2000 the bacterial population achieves its highest value before antibiotic suppression begins. This increased bacterial count makes antibiotics function for longer yet the suppression procedure takes more time because of the massive starting population.

The treatment response heavily depends on the carrying capacity value in each system. The bacteria expand to larger sizes when K_B increases thus requiring more time for antibiotic suppression to occur. The suppression duration stays shorter while the suppression occurs faster when carrying capacity is low. The length of antibiotic effectiveness as well as bacterial recovery potential depends directly on bacterial carrying capacity.

8. The bacterial carrying capacity (K_B) directly affects how antibiotic treatments behave during medicinal periods

The analysis proves that bacterial carrying capacity (K_B) rules the success patterns and temporal character of antibiotic treatments. Bacterial populations reach greater heights just before antibiotics control their growth when carrying capacity increases within the environment. Throughout the expanded growth phase antibiotic suppression becomes slower which extends treatment duration before the system becomes stable. An environment characterized by high bacterial carrying capacity needs stronger or more extended antibiotic treatments to efficiently suppress bacterial growth. The application of insufficient antibiotics because of fast breakdown or incorrect dosage allows germ survival together with resistance development potentials. To achieve success in high- K_B environments medical teams will probably require increased drug quantities combined with extended administration lengths or multiple drug therapies.



The carrying capacity reduction affects bacterial growth negatively by restricting their survival space through decreased resources or elevated competition elements. Antibiotic treatment eliminates bacterial populations more efficiently at lower magnitude while minimizing their overall numbers. Such condition leads to speedier system stabilization together with shortened interaction duration. Treatment outcomes improve when healthcare professionals administer reduced antibiotic amounts for shorter periods in low- K_B environments alongside diminished resistance risks and decreased side effects.

The finding demonstrates that elevated K_B levels produce greater bacterial counts which need enhanced therapeutic methods yet lower K_B conditions result in faster bacterial control.

The design of effective treatments requires practical knowledge about bacterial growth environments because they influence outcomes measurable by K_B . Linear levels of antibiotic use with longer durations should be considered for high- K_B circumstances although shorter treatment periods with lower doses prove sufficient in environments with low- K_B . Reduction of carrying capacity through combined therapeutic interventions and environmental interventions such as maintaining restricted nutrient availability can improve antibiotic effectiveness.

The analyzed scenario emphasizes the need to customize antibiotic treatments according to bacterial growing environments for maximum success against resistant bacteria.

9. Negative Influence of Increased Carrying Capacity (K_B) of the Bacterial Population

The ability of an environment to sustain its population defines its carrying capacity (K_B) which depends on several factors including resources and distribution of space alongside competition for them. The increase of carrying capacity (K_B) during bacterial infections produces multiple unfavorable impacts on treatment success along with patient health results.

The increase in carrying capacity enables bacterial populations to reach bigger numbers before antibiotic mediation begins thus extending the duration of bacterial growth and infection treatment delays. Prolonged growth from increased kidney crescent formation results in extended infections in addition to immunological system stress that creates worse symptoms and delayed patient healing conditions.

A high bacterial population requires longer or higher dosages of antibiotics in order to remove every last bacterium. Patient safety suffers from prolonged antibiotic exposure although it is essential because exposure generates extra healthcare expenses and patient treatment complexity along with gastrointestinal pain and allergic responses.

Elevations of K_B levels create a strong danger for bacteria developing antibiotic resistance. Due to larger populations the possibility increases that bacteria survive antibiotic treatment so they develop resistance mechanisms such as mutations or enzyme production that block antibiotics. The development of resistant bacterial strains becomes a major public health challenge because it reduces the effectiveness of traditional medications to the point of obsolete status.

Organizations with high K_B activity result in elevated bacterial spread that end up polluting the environment. Information about high bacterial activity in clinical and agricultural environments shows that the production of toxins with biofilm development and harmful metabolites contaminate equipment and surfaces and food supplies thus enhancing disease transmission risk.

The immune system becomes less effective as a result of high bacteria numbers. Pathogens exposed to high bacterial loads find additional time to avoid and block immune system responses which results in extended infections or repeated occurrence of these infections. Weakened immunity provides opportunistic pathogens the chance to invade resulting in additional complications for medical intervention.

High bacterial carrying capacity in environmental and industrial contexts such as water treatment or fermentation facility creates an environment suitable for undesirable or contaminating bacteria permitting product spoilage and contamination and necessitating extra operational costs to sustain system hygiene.

A few methods should be implemented to reduce these risks:

- (i). The use of effective antibiotics and combinations between drugs enables total bacterial suppression.
- (ii). The controls through environmental measures both minimize nutrients and space to reduce K_B development with subsequent bacterial growth containment.
- (iii). The patient's recovery time can be accelerated by strengthening their immune system with vaccines together



with probiotics and immunomodulators.

(iv).Environmental Control rates antibiotic resistance by assisting antibiotic treatment effectiveness while Antibiotic Stewardship establishes responsible antibiotic usage for slowing resistance development.

(v).The exploration of bacteriophage solutions and antimicrobial peptides shows potential to create highly specific bacterial targeting methods in healthcare.

The expansion of bacteria during infections creates severe complications for disease management because it enables bacteria to multiply faster and makes treatments less effective and creates more resistance. The optimization of treatment outcomes depends on KB understanding along with managing it since it protects both public health and industrial safety together with environmental protection.

10. Main Results and Conclusions

The models provide crucial knowledge about which changes in antibiotic performance and bacterial death speed and maximum bacterial number affect antibiotic dosage effects on microbial populations. The data shows that antibiotic potency leads bacteria to decline more rapidly thus improving treatment results. The treatment becomes more likely to generate bacterial resistance when dosage or treatment length is not effectively managed although it remains potent against microbial populations. Faster antibiotic decay patterns reduce the drug's treatment time span which allows bacterial recovery when patients stop taking antibiotics before completing their prescribed course. Bacterial treatment results heavily depend on the mathematical concept known as the carrying capacity (K_B) which determines bacterial population growth potential. Bacteria must attain high K_B levels before they can reach population densities that need extensive antibiotic duration coupled with strong antibiotic concentrations for full control.

The Numerical simulation demonstrates bacteria count reduction due to antibiotic action combined with the slow reduction of medicine presence leading to short-term antibiotic effectiveness. The identical state of human bodily conditions throughout the model demonstrates the ecological principle of amensalism which shows antibiotic exposure having negative effects on bacterial populations but not burdens for the human body host.

The model delivers an effective representation of antibiotic-bacteria relationships that demonstrates how improving drug strength combined with efficient decay rates leads to better therapeutic results. Therapeutic failures that occur due to poor control expose patients to serious bacterial resistance challenges. The study shows why analysts need to develop strategic antibiotic therapy plans while setting the groundwork for future investigations about immune responses and bacterial resistance mechanics as well as alternative therapeutic solutions which will improve infection treatment performance.

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