

Communication

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Communication

One Earth-One Health to Combat Bacterial Resistance Having Dual Mutation Pattern, Based on the Self-Regulation of Ecosystems

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Abstract

Antibiotic resistance (ABR) has emerged as a grave threat to human health, and a One Earth-One Health (OE-OH) concept was proposed for addressing this challenge in 2024. To elucidate and refine this concept, here a dual mutation pattern was put forward for bacterial resistance adhering to the principle of parsimony, integrating Lamarckian, Darwinian, and Niche construction theories. Subsequently, its theoretical foundation was clarified, together with a fundamental mathematical model for antibiotic resistance genes (ARGs) within ecosystems, based on the robust self-regulation and perpetual reconstruction of ecosystems. From this concept, it deduced that ABR and ARGs emerge 3.5 billion years ago and are ubiquitous across the globe prior to antibiotic use. For better understanding this concept, the self-regulation of the Earth's ecosystem on the generation, dissemination, and elimination of ABR and ARGs was sorted out and elucidated. Finally, several crucial measures are proposed for addressing the concern transcending this regulation due to antibiotic overuse, emphasizing the key role of utilizing the self-regulation of ecosystems.

Keywords: OE-OH; one health; mutation; ecosystem; antimicrobial agent; antibiotic; microbe; plant; climate; environment; combination; parsimony; Occam; Lamarck; Niche; Darwin

1. Introduction

Antibiotic resistance (ABR) has emerged as a serious threat to global public health and economic development, and the COVID-19 pandemic has further exacerbated this crisis [1–3]. It was showed that ABR has rapidly spread from diverse settings where antibiotics are used into surrounding environments [4,5]. Moreover, antibiotic resistance genes (ARGs) can be extensively detected in a wide range of water and soil environments [4–7], with their presence even being on the north slope of Mount Everest [8]. In light of these alarming trends, the World Health Organization (WHO) has projected that, without any intervention, antibiotic resistance would lead to 10 million deaths annually by 2050 [9,10]. In response to this crisis, the One Health Joint Plan of Action (2022–2026) (OH JPA) have developed, and appeal working together for the health of humans, animals, plants and the environment [7,11].

As is widely acknowledged, the use of antibiotics, particularly their overuse and abuse, has caused the crisis of ABR. However, it is worth exploring whether these reports can accurately reflect the actual situation of ABR. On the one hand, many studies, shaped by the interests of researches, focus on the spread and evolution of ABR among microorganisms and in the environment, understudying the self-regulatory capacity of the Earth's ecosystem in weakening and eliminating ABR and ARGs [12–15]. This self-regulatory capacity encompasses the complex interactions among humans, plants, animals, microorganisms, and the environment, as well as the functional redundancy

and removal of ARGs [4,16–18]. On the other hand, it is also worth contemplating whether the mere detection of ARGs implies that ABR has been transmitted to the sampling site. Both two aspects have prompted a more profound re-evaluation for the strategies and measures aimed at addressing ABR. Based on the discoveries of various laws on drug combination preventing ABR and the effects of numerous plant metabolites on reversing ABR [12,19–22], a One Earth-One Health (OE-OH) concept was put forward for preventing ABR, without details, on the 6th International Caparica Conference in Antibiotic Resistance 2024 (IC2AR 2024) and in a following publication [12,23].

The One Health (OH) concept posits that ABR encompasses multiple facets, including humans, animals, plants, and the environment, emphasizing the pivotal role of humans in combating ABR. In contrast, the OE-OH concept places greater emphasis on the robust self-regulatory capacity of the Earth's ecosystem and its sub-ecosystems in relation to ABR. Specifically, it accords equal importance to the generation, spread, weakening and elimination of ABR within the ecosystem, and regards the production and use of antibiotics as an intervention on the ecosystem's ABR dynamics. Herein, the theoretical foundation of this concept, together with many innovative prospectives, reasoning, deductions, and inductions concerning ABR and ARGs, are presented, from the OE-OH concept, as follows. Based on these, some distinctive strategies for combatting ABR are subsequently proposed and elaborated.

2. The OE-OH concept

2.1. A dual mutation pattern of bacterial resistance

In accordance with the principle of parsimony [24,25], also known as Occam's Razor, the mutation theory of bacterial resistance can be reconsidered. We believe that bacterial resistance predominantly engages in proactive evolution by adaptive mechanisms, and which is designed to avert the unnecessary expenditure of energy and resources that are typically associated with random mutations. This assertion aligns with Lamarck's theory which has also garnered support from recent research endeavors [26]. However, there may also be minor imprecise mutants during the course of proactive resistance mutations. Simultaneously, some ARG-carrying mutants can also emerge through the occasional and non-adaptive random mutations, and be passively screened by natural selection in accordance with Darwinian evolution. From these, ARG-carrying mutants originate from two distinct types of mutations, shown on Figure 1A. The dual mutation pattern of bacterial resistance, characterized primarily by proactive evolution and occasionally by passive selection, exhibits a striking congruence with the Niche construction theory which pertains to ecosystems [27,28]. From this pattern, the evolutionary origins of current ABR were deduced and shown on Figure 1B. Moreover, even although the proactive mutation is the primary pattern of microbial resistance to antibiotics, a large number of antibiotic-resistant microbes can still be found prior to exposure to antibiotics. This is due to the substantial accumulation of ARG-carrying pathogens in the Earth's ecosystem over a long period of time.

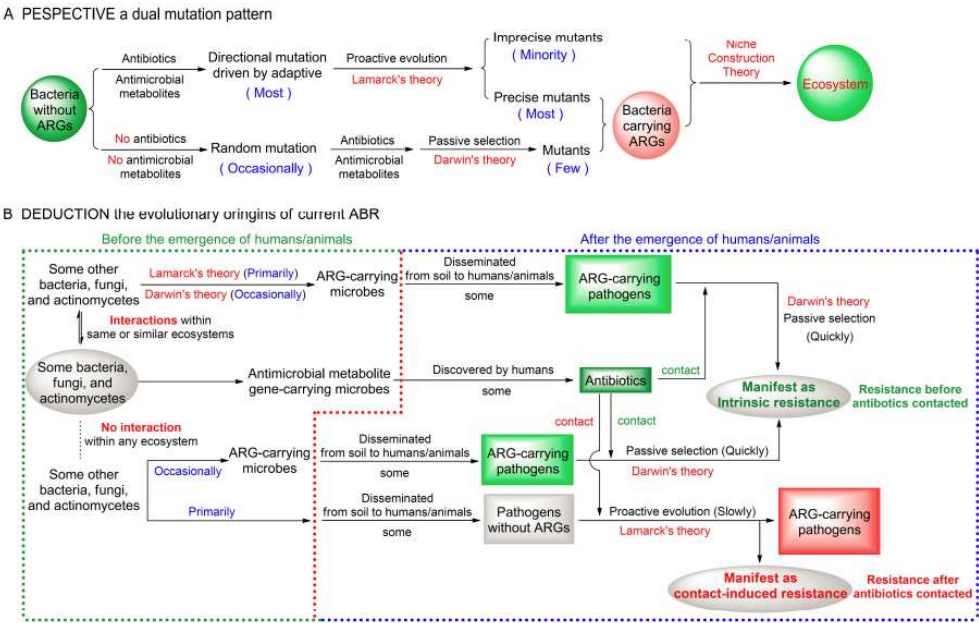


Figure 1. Dual Mutation Pattern of Bacterial Resistance. (A) The dual mutation pattern of bacterial resistance through proactive evolution and passive selection: ARGs, antibiotic resistance genes; (B) The evolutionary origins of current antibiotic resistance (ABR).

2.2. Theoretical logic of the OE-OH concept based on ecosystems

Inspired by the dual mutation pattern illustrated in Figure 1, it can be inferred that antimicrobial metabolites produced by microbes (some of which are termed antibiotics now), microbial resistance, and ARGs likely emerge concurrently with the formation of the microbial ecosystems. This is because they arise from the competition among microorganisms within ecosystems and are renewed as ecosystems undergo reconstruction [29–32]. Namely, ARG-carrying bacteria likely first emerged when certain microbial ecosystems were formed 3.5 billion years ago [33], and have been continuously spreading and renewing ever since (Figure 2). This was also supported by a recent publication [34]. Simultaneously, the Earth, including soil, various environments and all the organisms that inhabit it, can be regarded as a giant ecosystem composed of countless sub-ecosystems that operate through similar mechanisms. Therefore, the robust self-regulatory capacity and perpetual reconstruction of ecosystems, particularly those of the Earth's one [13–15], form the theoretical logic of the OE-OH concept. From this perspective, various aspects related to microbial resistance can be reexamined.

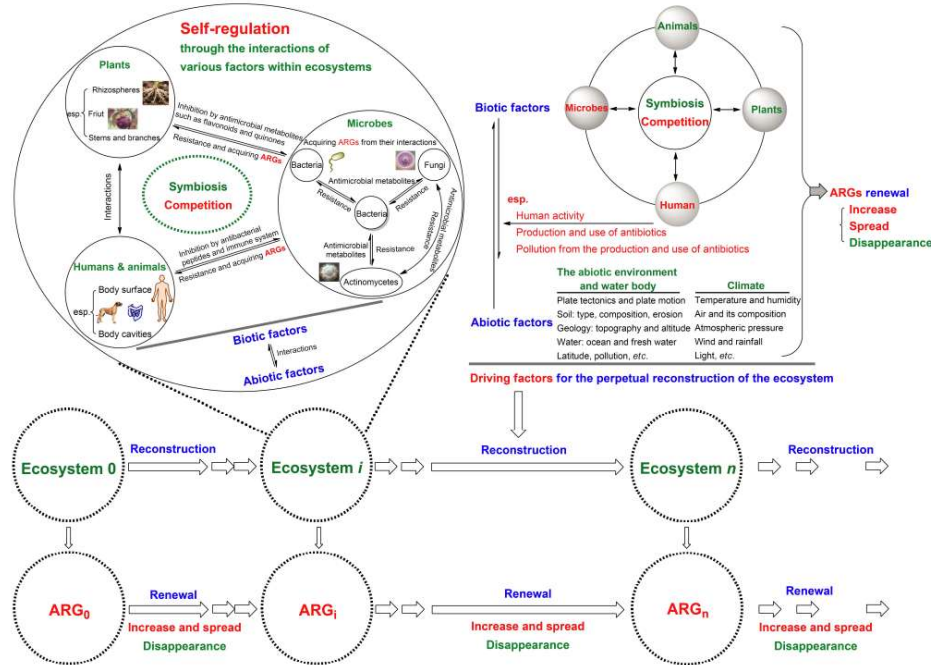


Figure 2. Schematic for the Theoretical Foundation of the One Earth-One Health Concept. This includes the theoretical logic and driving factors of ARG renewal within an ecosystem based on the robust self-regulatory capacity and perpetual reconstruction of ecosystems; the ecosystem can be the entire Earth's ecosystem or its various sub-ecosystems; ecosystems 0, i , and n indicate the ecosystem at different time points during its evolution, and their antibiotic resistance genes (ARGs) correspondingly renew with the perpetual reconstruction of the ecosystem.

2.3. A fundamental mathematical model for the ARGs renewing with the ecosystem

The OE-OH concept envisions the Earth as a giant ecosystem, intricately woven from a myriad of sub-ecosystems that operate through similar mechanisms. The amount of ARGs within an ecosystem can be articulated through a fundamental mathematical model as follows.

$$ARG_i = ARG_0 + (ARG_1^{In} + ARG_2^{In} + \dots + ARG_i^{In} + \dots + ARG_n^{In}) + (ARG_1^{De} + ARG_2^{De} + \dots + ARG_i^{De} + \dots + ARG_n^{De})$$

$$ARG_n = ARG_0 + \sum_{i=1}^n ARG_i^{In} + \sum_{i=1}^n ARG_i^{De}$$

Where ARG_i and ARG_n are the amount of ARGs at two time points (Figures 2 and 3) of the ecosystem which can be the Earth's ecosystem or its various sub-one, and time point i can be equal to n ; ARG_0 can be the amount of ARGs at any time point while time points i and n are more than or equal to time point 0, and especially the amount of ARG_0 is zero before the microbial ecosystem emerged on the Earth; ARG^{In} is the increased amount of ARGs within the ecosystem, for example ARG_1^{In} is that from time point 0 to 1; ARG^{De} (defines as negative value) is the decreased amount of ARGs within the ecosystem, for example ARG_1^{De} is that from time point 0 to 1; $\sum_{i=1}^n ARG_i^{In}$ is the sum of the increased amount of ARGs from time point 1 to n , and $\sum_{i=1}^n ARG_i^{De}$ is the sum of the decreased amount of ARGs from time point 1 to n .

3. ARG analyses from the OE-OH concept based on ecosystems

3.1. ARGs emerging prior to the emergence of humans and existing everywhere in the world

Antimicrobial metabolites are a category of natural products that generate from the competition for ecological niches among microorganisms within ecosystems or in response to survival stress [29–31]. From the evolutionary history of the Earth, it is known that microbes emerge about 3.5 billion

years ago, and by that time, diverse ecosystems teeming with microbial communities had already taken shape [33,34].

After a long period of evolution, there are sufficient reasons to infer that the structural skeletons of most clinical antibiotics can be biosynthesized by environmental microorganisms. This can be confirmed by the fact that the structural skeletons of clinical antibiotics were mostly discovered from soil microorganisms [29]. In other words, microorganisms that carry the genetic information for biosynthesizing the structural skeletons of most clinical antibiotics, including microbial strains belonging to the same or different genera and species, are widely distributed in various sub-ecosystems of the Earth. Even synthetic quinolone antimicrobial agents bear a resemblance in structural framework to naturally occurring compounds such as plant-derived flavonoids and benzofuranones [12,35]. This is also a reason that natural products with antibacterial activity can be continuously discovered from environmental microorganisms. Likely, the genetic information of microorganisms producing these natural products has existed on the Earth before the emergence of humans [36], while only was discovered and excavated after entering into the 20th century.

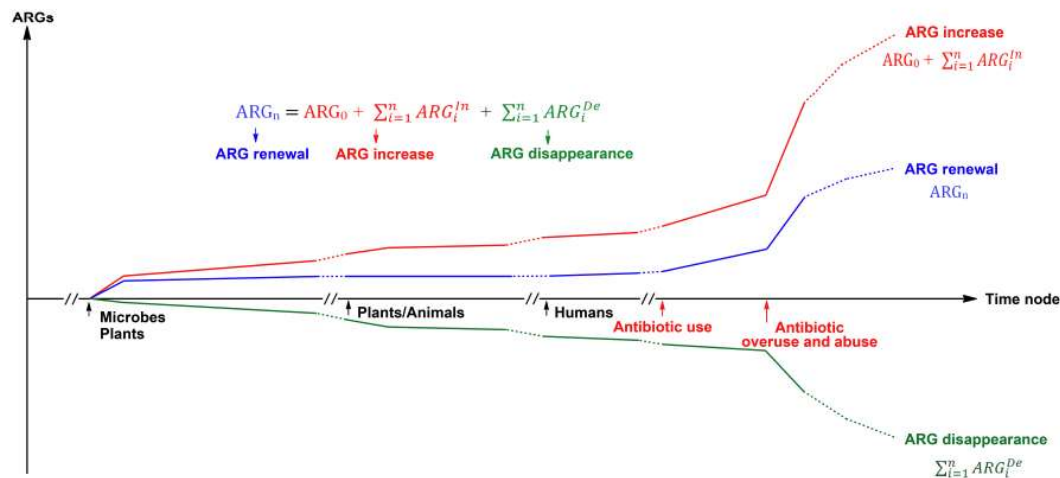


Figure 3. A schematic for the amount of antibiotic resistance genes (ARGs, y) within an ecosystem changing with typical evolutionary time nodes (Time, x), according to a fundamental mathematical model. The ecosystem can be the entire Earth's ecosystem or its various sub-ecosystems, and the typical time nodes include the emergence of microbes, plants, animal, and humans, and the use of antibiotics by humans.

It is reported that today's pathogenic microorganisms originate from the soil [37,38]. Therefore, clinical pathogens should be widely distributed across various ecosystems on the Earth and likely prior to the emergence of humans (Figure 3). Since antimicrobial metabolites generated before 3.5 billion years ago, it is reasonable to deduce that, due to microbial competition within ecosystems, the ARGs of pathogenic microorganisms evolved in response to the survival stress from antimicrobial metabolites (some of which are now used as antibiotics) produced by other environmental microbes may had been already emerged at that time.

As the Earth's ecosystem and its diverse sub-ecosystems evolve and undergo reconstruction driven by a variety of biotic and abiotic factors [39], new ARGs are perpetually emerging. Moreover, ARGs are continuously spreading and renewing across every corner of the Earth. Therefore, it can be inferred that microorganisms responsible for producing the structural skeleton of certain antibiotics, along with pathogens carrying corresponding ARGs, are located in specific ecosystems. When antibiotics are isolated from soil or marine microbes, it is likely that these pathogens have already encountered these antibiotics during the evolutionary process of the Earth's ecosystem. Through proactive adaptive mutations and the acquisition of heritable ARGs, these pathogens have also developed resistance to these antibiotics. This may explain why ARG-carrying pathogens can sometimes be detected shortly after the introduction of new antibiotics to the market [40], or before they appear to have come into contact with the corresponding antibiotics, sometimes even before the

3.2. ARGs by the self-regulation of ecosystems before the use of antibiotics

As shown in [Box S1](#) in supplemental information, a wide range of biotic and abiotic factors, including the abiotic environment, water bodies, climate, microbes, plants, animals and humans, can impact the renewals of ARGs within the Earth's ecosystem and its various sub-ecosystems. Owing to the sufficient self-regulation, self-balancing and buffering capacities of the Earth's ecosystem [12–15], the evolution of ABR and ARGs has historically maintained a balanced and controllable state prior to the industrial production and use of antibiotics by humans. However, the situation has become increasingly worrying due to the extensive use of antibiotics, particularly their overuse and abuse in clinical settings, livestock, poultry farming, and aquaculture. This was also reflected in the rapid increase in ABR and the widespread dissemination of ARGs after the industrial production and use of antibiotics.

The OE-OH concept based on the self-regulation of the Earth's ecosystem for ABR and ARGs.

$$\text{ARG}_n = \text{ARG}_0 + \sum_{i=1}^n \text{ARG}_i^{\text{In}} + \sum_{i=1}^n \text{ARG}_i^{\text{De}}$$

Factors for the weakening and elimination of ARGs (ARG^{De})

Abiotic factors

The abiotic environment and water body

Plate tectonics and plate motion, geological disaster
Soil components, dust and air [6,85,97]
Dilution and/or elimination of antibiotics and ARGs [55,81,98, 99]
Dilution, decrease and disappearance of the selective pressure [48]
The killing and clearance of ARGs and antibiotic-resistant pathogens [81,82,100–102]

Climate

Rainfall, wind, global warming, and drought [39,93,100]
Biotic factors influenced by climate change and climate extremes [48,94,95]



Biotic factors

Microbes

- Fitness costs [47]
- Negative selection, and disappearance in selection pressure [16-18,48]
- Genetic incompatibility inhibiting the horizontal transfer of ARGs [51,120]
- The degradation of the interaction among various microbes to antibiotics [52,83]
- The killing and inhibition of other microbes to pathogens within ecosystems [4]

Plants

Plants

Plants

- The decrease in plant diversity [62]
- The ARGs enrichment in the rhizosphere of plants [108]
- The activation to ARG expressions by plant antibacterial metabolites [18]
- The interactions between plants and microbes

Animals

- Activities and migration
- Foraging and excretion [109–115]
- The activation to ARG expressions by antimicrobial peptides [18]

Human and human activity

- Daily activities, migration, travels, diet, and excretion [3,37,109,110,112,114,116–118]
- The activation to the ARG expressions by antimicrobial peptides [49]
- Population gathering and domestic sewage [4,58,59]
- The use and abuse of antimicrobial agents in medical activities, livestock, poultry farming, and aquaculture, etc. [4,48,53]
- The use of air and environmental disinfectants [119]
- The pollution of air and water from the production and use of antibiotics and environmental disinfectants [3,4,54–57,119]
- The impacts of human activities on all biotic and abiotic factors that generate and spread ABR and ARGs in the Earth's ecosystem [60–65]

The increase in plant diversity [62]

The degradation of antimicrobial agents by plants [84,121,122]

Sensitization of antimicrobial resistance by plant antibacterial metabolites [12,123]

The killing and clearance of plant antibacterial metabolites to drug-resistant pathogens [4,72]

Animals

- The killing and clearance of animal body to drug-resistant pathogens including the immune system, antibacterial peptides, beneficial microorganisms, etc. [124]
- Foraging and the sensitization of the intestinal microbial ecology to drug-resistant pathogens [4]

Human and human activity

- The killing and clearance of human body to antibiotic-resistant pathogens [49,50,71,125] including the immune system, antibacterial peptides, beneficial microorganisms, etc.
- Diet and the sensitization of gut microbial ecology to antibiotic-resistant pathogens [12,126]
- Degradation, reduction and removal of antibiotics in waste residues and water from medical activities, livestock, poultry farming, and aquaculture, etc. [81,83,84]
- Disinfection and inactivation of antibiotic-resistant pathogens
- All other possible human activities on biotic and abiotic factors that clear antibiotics and decrease ARGs within the Earth's ecosystems [84,81,124,127]

Note: OE-OH, One Earth-One Health; ABR, antibiotic resistance; ARGs, antibiotic resistance genes; ARG^{In}, the increased amount of ARGs within the ecosystem; and ARG^{De}, the decrease amount of ARGs within the ecosystem.

3.3. Impact of antibiotic use on the self-regulation of ecosystems to ARGs

In the 20th century, many secondary metabolites with antimicrobial activities at low concentrations were discovered from environmental microorganisms, particularly actinomycetes, fungi, and bacteria, across diverse habitats such as land, oceans, and the body surfaces and feces of animals and humans [29,31]. Some of these metabolites and their derivatives have been developed as clinical antibiotics. In fact, the genetic information of microorganisms producing these antibiotics, together with the corresponding ARGs carried by pathogens resistant to these antibiotics, was already generated long ago, and can be considered as the products of competition among various microorganisms during the Earth's evolutionary history. Although most of the clinical antibiotics currently in use are structural derivatives of these natural antibiotics, they share similar structural skeletons with corresponding naturally sourced antibiotics. Consequently, the information of their corresponding ARGs carried by pathogens has existed in nature for a long ago. Moreover, pathogens carrying these resistance genes have spread globally, with some disseminating through soil and others colonizing specific parts of the human body [37].

From the above, the widespread use of antibiotics across various domains, including medical practices, livestock breeding, poultry farming, and aquaculture, can be considered as a human intervention on the evolution of ARGs within the global ecosystem [52]. Besides general human activities, as well as the interactions between the human body and microbes, have been driving the spread of ARGs (Box 1) prior to the use of antibiotics, several key activities associated the industrial production and use of antibiotics by humans have led to a sharp increase in ABR and the rapid spread of ARGs. These activities are as follows: 1) The use, overuse and abuse of antibiotics in medical practices, livestock, poultry farming, and aquaculture, etc. [4,48,53]; 2) The pollution of the Earth's environment caused by wastewater discharged from the settings of antibiotic production and use [3,4,7,53–57]; 3) The excessive aggregation of human population and the large amounts of domestic sewage generated under conditions of antibiotic overuse and misuse [4,58,59]; 4) The impacts of other human activities on all biotic and abiotic factors that contribute to the generation and spread ARGs within the Earth's ecosystem [60–65].

Theoretically, the wider the application scope of antibiotics and the greater their usage, the larger the intervention intensity on ecosystems. When the intervention intensity keeps within a specific and controllable range, the Earth's ecosystem and its myriad sub-ecosystems have sufficient self-regulation capabilities to restore or reestablish a new balance (Box 1). But if the intervention intensity exceeds the self-regulation capacity of ecosystems, the balance of these ecosystems will inevitably be disrupted, endangering larger ecosystems and even the entire Earth's ecosystem [13,66]. Therefore, our endeavors to discover new antibiotics seem to have the potential to solve the problem of antibiotic shortage caused by ABR, however they are merely a passive defense strategy even if the development of new antibiotics can be accelerated with the assistance of artificial intelligence (AI) [67]. Although

AI has the potential to predict microbial resistance to existing antibiotics and facilitate a proactive defense in the future, the struggle between humans and microbes is at most evenly matched. More significantly, the damage to various ecosystems caused by the overuse and abuse of antibiotics, together with the impact and deterioration of new ecosystem reconstruction on human living conditions, should arouse sufficient attention in this struggle.

Therefore, if the overuse and abuse of antibiotics are not controlled, the approval and application of new antibiotics will only accelerate the spread of ABR and ARGs. This will lead to the continuous destruction of larger and more ecosystems centered on the application environment. Moreover, various ecosystems containing more pathogens carrying ARGs will be restructured, ultimately posing a threat to the survival and development of humans. Thus, it is imperative to implement scientific and rational measures to control the spread of ABR and ARGs, for maintaining the balance of the Earth's ecosystem and its various sub-ecosystems.

4. Measures combating ABR from the OE-OH concept based on ecosystems

As previously stated, the use of antibiotics can be regarded as an intervention on ecosystems from the OE-OH concept. Thereby, a counteracting intervention aimed at preserving the balance of ecosystems should be taken for effectively combating ABR (Figure 4) [68]. Simultaneously, the self-regulation and -balance capabilities of ecosystems can be fully understood and utilized for the risk evaluation on some measures taken for the research and development, application and management of antibiotics. Learning from the approach of problem management [69,70], some crucial measures from the OE-OH concept, with the support of literature, are suggested as follows:

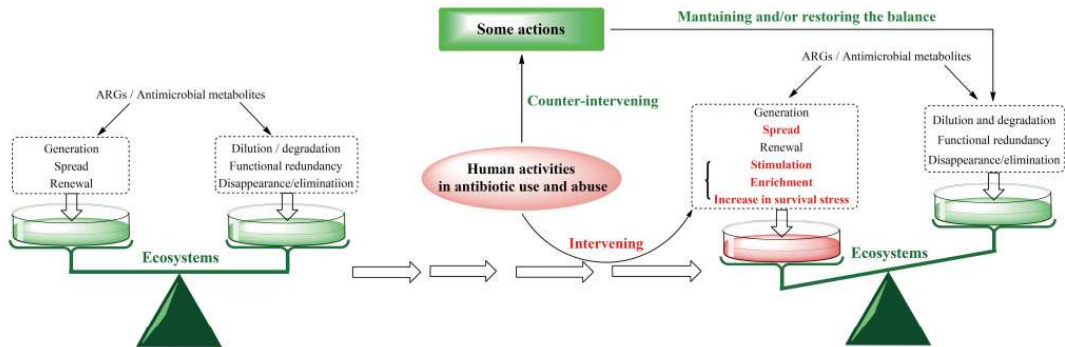


Figure 4. Analysis schematic of some imperative actions taken to offset the imbalance risk of ecosystems caused by the antibiotic use exceeding the self-regulation and balancing capacity of ecosystems, for combating the ABR from the OE-OH concept. ARGs, antibiotic resistance genes.

4.1. Minimizing antibiotic use, while fully utilizing the regulatory role of plants

From the OE-OH perspective, the bodies of humans or animals themselves can be regarded as ecosystems with sufficient self-regulation capabilities. For instance, their immune systems [49], antimicrobial peptides [71], colonized probiotics, and the competition among microorganisms within the body's ecosystem can eliminate infected pathogens, including those are antibiotic-resistant. Meanwhile, many plants, such as traditional Chinese medicine and ethnic medicines, also have the potential to regulate the balance between the bodies of humans or animals and microbes [12,72,73]. This has been evidenced in China during the COVID-19 pandemic [74]. Therefore, it is entirely feasible to reduce the use of antibiotics through utilizing the self-regulation and self-balance abilities of both humans and animals themselves, as well as the regulatory effects of plants on these abilities. Furthermore, even in cases where the bodies of humans and animals are infected, the balance between them and microbes can still be regulated or restored by plants. This can help to mitigate the progression of microbial infections and, to the greatest extent possible, avoid the unnecessary use of antibiotics.

4.2. Minimizing antibiotic emissions, while fully utilizing the self-regulation of ecosystems

From the OE-OH perspective, microbial resistance predominantly follows the proactive pattern of adaptive evolution, occasionally the passive one of random mutation by natural selection. As the Earth continues to evolve and develop, ARG-carrying pathogens that are widely distributed can be activated, screened, and enriched under the stress of antibiotics. Consequently, the emission of antibiotics into the surrounding environment not only stimulates the overexpression of ARGs in pathogens and enriches the information of ARGs, but also enables susceptible bacteria to proactively evolve into resistant pathogens. Therefore, it is crucial to minimize the emission of antibiotics and ARGs.

Alternatively, from the OE-OH perspective, the transmission processes of antibiotics and ARGs also involve their dilution, redundancy, or disappearance by various ecosystems. Therefore, when effective control is challenging and emissions are unavoidable, the weakening and elimination capacities of ecosystems to antibiotics and ARGs can be fully utilized [73,75–77]. At this moment, scientific and rational measures should be adopted, based on the risk management [78], to implement graded emissions for keeping the emissions of antibiotics and ARGs within the controllable and balanced range of ecosystems, minimizing the damage caused by excessive accumulation of antibiotics and ARGs to the original ecosystem.

4.3. Avoiding the excessive aggregation of population

From the OE-OH perspective, the entire Earth's ecosystem possesses a robust self-regulation capacity to manage the generation, dissemination, enrichment, dilution, weakening, and elimination of ARGs, thereby maintaining its equilibrium. However, the overuse and abuse of antibiotics by humans will lead to a continuous enrichment of ARGs and stimulate their proliferation in the environment, resulting in an increasing diversity and abundance of ARGs. If the population becomes excessively concentrated at this moment, it will significantly surpass the capacity of various biotic and abiotic factors (Box 1) to weaken and eliminate ARGs, as well as the self-regulation ability of ecosystems, leading to an excessive accumulation of ARGs in ecosystems centered around the population gathering areas. Therefore, it is crucial to avoid excessive population aggregation [76]. Specifically, the scale of cities should be kept within reasonable limits, and the urban layouts should be appropriately decentralized. This can also be indirectly proved by the transmission patterns of the COVID-19 pandemic.

4.4. Accelerating the antibiotic reserve based on the understanding for microbial defense mechanisms

From the OE-OH perspective, we can gain a comprehensive understanding of the proactive defense mechanisms of microbes in ecosystems, for developing new antibiotics that are less likely to encounter resistance. Additionally, it is also encouraged to develop new antibiotics with high specificity and minimal disruption to the gut microbes and organismal ecosystems. Meanwhile, it is essential to thoroughly explore the unknown ARGs within ecosystems. By doing so, we can utilize AI technology to predict potential ABR. Based on the potential mechanisms of microbial resistance, the development of new antibiotics that are difficult for pathogens to develop resistance should be expedited to ensure a sufficient reserve of these new antibiotics. In addition, from a policy standpoint, the protection period of patents for new antibiotics can be extended, for reducing the unnecessary use of new antibiotics.

4.5. Encouraging antibiotics used in combination with plant-derived antimicrobial ingredients

From the OE-OH perspective, the increased application of new antibiotics will accelerate the spread and enrichment of ABR and ARGs if the overuse and abuse of antibiotics are not controlled. Therefore, it is imperative to use antibiotics rationally. Among various strategies for the rational use of antibiotics, combination therapy has the advantages of cost-effectiveness in enhancing the efficacy of antibiotics, reversing microbial resistance, and extending the life cycle of antibiotics, buying more

time for the development of new antibiotics. This can be also proved by the clinical practice of combination therapy, such as the combination of sulfamethoxazole and trimethoprim, β -lactamase inhibitors and β -lactam antibiotics, and multiple anti-tuberculosis drugs. Therefore, combination therapy is highly commendable [12,52]. However, it is noteworthy that an inappropriate antibiotic combination would instead increase the risk of ABR, due to the effect preventing resistance is associate with the fractional inhibitory concentration index, as well as the proportion and concentration of two antibiotics in the combination [19,20,79].

Antibiotics are derived from the competition among microorganisms. Both bacteria/fungi producing the structural skeleton of antibiotics and pathogenic bacteria are classified as microbes. As a result, their individual defense mechanisms are familiar to each other, making it easier for pathogens to develop resistance to antibiotics in the combination. However, the antimicrobial ingredients of plants originate from the interaction between microorganisms and plants within ecosystems, and the defense mechanisms between plants and microbes are less familiar to each other. Simultaneously, plant-derived antimicrobial components generally exhibit weaker antibacterial activity and smaller stresses on microbial survival compared to antibiotics. Therefore, it is more challenging for microbes to develop resistance to them [20]. Moreover, the combination of plant-derived antibacterial components and antibiotics often has a wide range of synergistic effects [12], and the impact on gut microbes is also milder. Therefore, plant-derived antibacterial components are ideal candidates for combination therapy with antibiotics.

4.6. *Simulating the elimination of antibiotics and ARGs within ecosystems*

From the OE-OH perspective, ecosystems have robust capacity to regulate ABR, encompassing the dilution, weakening and elimination of ARGs. Therefore, it is highly encouraged to simulate the elimination of antibiotics and ARGs within ecosystems based on a thorough understanding of their self-regulation mechanisms [68,80]. For instance, employing bacterial ecology to combat ARG dissemination [4], utilizing photocatalysis-enhanced constructed wetlands to remove ARGs [81], simulating sunlight-induced inactivation of tetracycline-resistant bacteria [82], and leveraging bacteria-microalgae-fungi symbionts or plants to remove antibiotics [83,84]. Additionally, these ecological simulation methods and technologies can also, to the greatest extent possible, avoid the potential adverse effects on ecosystems that may be caused by the measures taken.

5. Methods

5.1. *The OE-OH concept*

The OE-OH concept was put forwards from the previous results and the sufficient self-regulation ability of the Earth's ecosystem in the evolution of ABR [12,23]. Here this concept has been further defined, improved and clarified using logical, reasoning and deductive methods based on the principle of parsimony [24,25], involving the understanding integration of Lamarck's theory, Darwinian evolution, and Niche construction theory. It includes dual mutation patterns of bacterial resistance, theoretical underpinnings of the OE-OH concept based on ecosystems, and basic mathematical model for the ARGs renewing with the ecosystem. The literature supporting the reasoning and deduction, together with all other literature, was unsystematically searched from PubMed database and Google academic search engine, using various relevant keywords. Furthermore, some highly persuasive references in the obtained literature were also tracked.

5.2. *Analyses of ARG generation, spread and elimination from the OE-OH concept*

From the OE-OH concept, the generation, spread and elimination of ARGs along with different time nodes of the Earth's evolution were analyzed using reasoning, deductive and inductive methods based on the self-regulation of ecosystems, together with the supporting of literature also searched

from PubMed database and Google academic search engine. These especially include the emergence and distribution of ARGs emerging before humans, the ARG regulation by ecosystems such as its generation, spread, weakening and elimination of ARGs before the industrial production and use of antibiotics, the sharp increase in ARGs after the industrial production and use of antibiotics together with which impact on the self-regulation and self-balance of ecosystems for ARGs.

5.3. Measures combating ABR from the OE-OH concept based on ecosystems

Regarding the use of antibiotics as an intervention on ecosystems, some important measures for the research and development, application and management of antibiotics are suggested, from the OE-OH prospective, for maintaining the balance of ecosystems regulating on ARGs, learning from the approach of problem management [69,70].

6. Future directions

Drawing on the OE-OH concept, the following research directions are proposed for future exploration: (1) Referred to Lamarck's theory and Niche construction one, emphasizing the interactions among various factors in host ecosystems and strengthening researches on the proactive defense mechanisms of microbe, for developing new antibiotics with strong selectivity that cause minimal disruption to human ecosystems; (2) Conducting in-depth investigations into ARGs in problem-oriented samples from both designed terrestrial and marine environments. This not only can help to elucidate the dissemination of ARGs, but also can provide additional evidence for understanding the Earth's evolution, plate tectonics, and human migration; (3) Emphasizing the crucial role of the self-regulation of ecosystems on addressing ABR, strengthening researches on the regulation of plant on the ecosystem of human body preventing microbial infection, and encouraging the research and development of antibiotics in combination with plant-derived antimicrobial ingredients; (4) Increasing efforts to study the dilution and degradation of antibiotics in ecosystems, as well as the weakening and elimination of ARGs, and developing methods and technologies that simulate the elimination of antibiotics and ARGs within ecosystems; (5) Based on the self-regulatory capacity of ecosystems in the elimination of antibiotics and ARGs, conducting researches on the schemes of population distribution and urban settlements for combatting ABR.

7. Conclusion

The OE-OH concept has been clarified and refined, which includes: (1) A dual mutation pattern of primarily proactive evolution aligning with Lamarck's theory and occasionally passive selection in accordance with Darwinian evolution theory for bacterial resistance mutation, adhering to with the principle of parsimony; (2) The theoretical logic of this concept based on the robust self-regulatory capacity and perpetual reconstruction of ecosystems, and a fundamental mathematical model for the renewal of ARGs within the ecosystem; (3) The farther the evolutionary distance between species, the weaker the antagonistic effect of the secondary metabolites they produce on each other, and the more difficult it is for them to develop resistance to each other. Derived from this concept, it deduced that ABR and ARGs emerge 3.5 billion years ago and exist in every corner of the Earth prior to the use of antibiotics by humans. Regarded as an intervention on ecosystems, the use of antibiotics, particularly their overuse and abuse, have posed a concern that transcends the ecosystem's self-regulatory capacity. Based on these, several crucial measures derived from the OE-OH concept are proposed for combatting ABR. These measures place a strong emphasis on simulating and leveraging the self-regulatory mechanisms of ecosystems, advocating for the minimization of antibiotic use and emissions, preventing excessive population aggregation, and encouraging antibiotics used in combination with plant-derived antimicrobial ingredients. Finally, it is essential to implement the OH Joint Plan of Action from the OE-OH perspective, emphasizing the key role of utilizing the self-regulation of ecosystems on addressing ABR.

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