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Survival Strategies of Unicellular Microorganisms: Substance Acquisition and Energy Metabolism

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Abstract. Unicellular microorganisms are widespread in almost all natural ecosystems and face environmental stresses. Analyzing their adaptation process has a significant influence on microbial ecology. These microorganisms deeply affect chemical recycling in the global ecosystem. This research analyzes the survival strategies of three types of unicellular microorganisms: autotrophs, heterotrophs, mixotrophs, and explains the different metabolic ways under long-term lack of resources. Result shows that microorganisms use structural and physiological rebuilding to survive in resource-limited conditions, but long-term resource consumption may limit their recovery. Autotrophic microorganisms fix inorganic carbon to make organic compounds, and this process may consume a lot of energy. Mixotrophic organisms combine these two metabolisms, but this may bring an extra energy burden. The research suggests that no strategy has absolute advantages, and all these adaptations may bring metabolic costs. This conclusion can explain how microorganisms in natural environments adapt to fluctuations in nutrient conditions.

Keywords: Unicellular microorganisms, nutrient acquisition, energy metabolism, metabolic adaptation, survival strategy

1. Introduction

Unicellular organisms are widely spread in ecosystems and always face extreme environments. These conditions include a lack of nutrients. Compared with multicellular organisms that have specific organs and tissues to adapt to pressure, unicellular microorganisms rely on the cell membrane and metabolic pathways in the cell to transport substances and carry out metabolism. To live in adverse conditions, unicellular microorganisms need to activate physiological adaptation mechanisms. Otherwise, they cannot survive. While these adaptations may bring both advantages and disadvantages, the balance between these survival benefits and energetic costs ultimately determines microorganisms' adaptations [1].

Many experiments suggest how unicellular microorganisms adapt to extreme environmental conditions. Researchers illustrate how microorganism metabolism changes under nutrient-deficient conditions and compare how heterotrophic and autotrophic microorganisms use their specific physiological advantages to survive. Through these experiments, scientists confirm that microorganisms possess their own survival mechanisms. However, recent research has obvious

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limitations. Many studies only target a single microorganism type for discussion but rarely examine different types of unicellular microorganisms. This limits conclusions regarding the disadvantages and advantages of each nutritional strategy, as well as which environments suit specific survival capabilities.

Traditionally, many studies have treated substance acquisition and energy metabolism as separate processes. However, under nutrient limitation, these two processes are tightly coupled rather than independent. The operation of substance transport systems consumes ATP, while cellular energy status in turn regulates the expression and activity of these transporters. This coordination between substrate uptake and energy metabolism ultimately determines microbial fitness and competitive adaptability under environmental stress.

In addition, most current experimental evidence derives from laboratory settings that differ substantially from natural complex ecosystems. Laboratory experiments generally cannot replicate environments containing multiple simultaneous stressors, nor can they fully represent the competitive, cooperative and mutational interactions that occur among microorganisms in natural systems. Because single microorganisms do not survive independently, laboratory-based conclusions cannot be extended uncritically to all types of natural environments [2].

This paper explores how single-celled microorganisms get materials and energy to stay alive. It sums up their different survival behaviors, inner working rules, the related strengths and weaknesses. Besides, this review tries to find better ways to study single-celled organisms and discuss how these findings can help real-world applications.

For example, in wastewater treatment, single-celled microorganisms take away nutrients and pollutants from water. This shows how they get materials and energy when nutrients are scarce. In bioremediation, knowing their tolerance limits helps people choose proper microbial groups for different polluted environments.

These three kinds of single-celled microorganisms represent three different nutrient-use types: a typical autotroph, a mixotroph, and a heterotroph. By comparing these groups, this review directly looks at their special survival behaviors and the strategies they use to get materials and energy under stress. It also finds common survival methods and unique strengths of each group. However, most current data comes from lab experiments. So these conclusions are not final.

2. Heterotrophic microorganisms

Unicellular microorganisms may face changeable living environments. For example, sometimes they are nutrient-rich, sometimes they are nutrient-starved; sometimes light intensity is high, while at other times it is low. This review categorizes unicellular microorganisms into three nutritional types: heterotrophs, autotrophs, mixotrophs, and analyzes how each type survives in stable or extreme environments.

Heterotrophic microorganisms cannot fix inorganic carbon dioxide to synthesize organic molecules. They must acquire both carbon and energy from external environments. They can be further divided into chemoheterotrophs and photoheterotrophs. Chemoheterotrophs, such as E. coli, most bacteria, and fungi, obtain carbon and energy by oxidizing organic molecules including sugars, proteins, and lipids. Therefore, heterotrophs function as consumers or decomposers in ecosystems rather than primary producers. Different from autotrophic and mixotrophic microbes, heterotrophs lack endogenous carbon fixation pathways, making their metabolic activity fully dependent on

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exogenous organic substrate availability. This core physiological trait defines their unique stress response logic and ecological niche in fluctuating environments.

2.1. Survival strategies of E. coli under nutrient fluctuation

Escherichia coli serves as a classic model heterotrophic microbe in ecological and metabolic research. E. coli, unlike the stable nutrient-rich culture conditions used in laboratory experiments, natural habitats such as soil, water, and intestinal environments frequently undergo drastic nutrient depletion, making long-term starvation the dominant living state for wild populations [1]. This section systematically elaborates the multi-dimensional adaptive mechanisms of E. coli under fluctuating nutrient availability, focusing on the coupling strategy of substance acquisition and energy metabolism, as well as the inherent trade-offs of each adaptive behavior.

E. coli exhibits completely divergent metabolic modes in nutrient-rich and nutrient-starved environments to adapt to habitat fluctuations. Under sufficient nutrient conditions, cells prioritize rapid proliferation, with high-speed substrate transport, vigorous glycolysis and protein synthesis, and minimal energy reserve accumulation to maximize population growth rate. In sharp contrast, severe nutrient limitation triggers comprehensive metabolic depression. Cells actively downregulate energy-intensive anabolic processes including cell division and macromolecular synthesis, retaining only basic catabolic pathways to reduce basal ATP consumption [3]. This metabolic slowdown is the core energy-saving strategy for heterotrophic microbes to resist starvation stress.

To sustain long-term survival under extreme oligotrophic pressure, E. coli relies on two core compensatory mechanisms: endogenous nutrient recycling and directional adaptive mutation. When large numbers of cells die under starvation, lysed bacterial bodies release massive intracellular organic substances, including amino acids, polysaccharides, and lipid molecules. E. coli surviving cells significantly upregulate the expression of extracellular hydrolases and low-affinity general substrate transporters, which efficiently decompose and scavenge residual organic matter in the microenvironment. This intraspecific nutrient recycling system builds a self-circulating metabolic microenvironment, effectively relieving exogenous nutrient deficiency and maintaining basic cellular vitality.

Except for passive nutrient cycles of nutrients, adaptive mutation is a long-term strategy and helps them adapt to continuous pressure. Lack of nutrients will inhibit DNA repair system activity and increase metabolic gene mutation frequency [4]. Many random mutations are neutral or harmful, and they may be eliminated in the total population screening. The mutations that can increase transport frequency, reduce energy consumption, or increase the ability to face pressure will accumulate and be inherited [4]. Through many generations of selection, the whole population of microorganisms may adapt to nutrient-poor environments. A noticeable point is that hunger survival ability and pressure tolerance are two independent adaptations. For heterotrophs, they build an important metabolic balance under nutrient deficiency. Groups of genes may be activated, and these genes, under hunger states, cannot increase the cell survival rate. In contrast, their core function is to optimize metabolic waste and store energy substrates so they can reduce the time period for cell regeneration and recovery. This shows that microorganisms' adaptability is not limited to simple survival and includes the possibility of regaining competitive advantages after stress is relieved.

In long-term nutrient starvation conditions, many E. coli cells can survive but enter a non-culturable state, known as VBNC [5]. In this state, cells can maintain complex cell-membrane structures and residual metabolic activity but lose the ability to form colonies. This dormant state represents a passive adaptation rather than cell death. It drastically reduces energy consumption and

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greatly improves the survival rate of microorganisms under nutrient-limited conditions. However, this strategy carries notable risks. Prolonged dormancy leads to the degradation of certain metabolic enzymes and transport systems. Even after nutrient replenishment, the recovery cycle can be extremely long. Therefore, survival alone cannot fully reflect the adaptability of heterotrophic microorganisms; their potential for growth recovery must also be evaluated.

Persistent starvation also forces cells to undergo comprehensive cellular structural remodelling, which brings unavoidable energetic burdens [3]. Cells simplify redundant intracellular structures, downregulate the synthesis of non-essential proteins, and rearrange transmembrane transport systems to match low-nutrient metabolic modes. Although these modifications effectively reduce energy consumption in the short term, the remodelling process itself consumes a large amount of intracellular ATP and residual nutrients. With the continuous depletion of endogenous energy reserves, the metabolic efficiency of cells declines irreversibly, leading to slow population mortality under ultra-long-term starvation. This fully reveals the essential limitation of heterotrophic microbes: all adaptive strategies rely on exogenous resources, and no completely self-sustaining metabolic mechanism can offset extreme nutrient deficiency.

2.2. VBNC state and post-stress recovery trade-off

The viable-but-non-culturable (VBNC) state represents a sophisticated dormant adaptive strategy unique to heterotrophic microorganisms under prolonged nutrient stress, rather than simple metabolic stagnation. When external organic carbon and nitrogen sources are severely depleted, E. coli actively shuts down cell division pathways and high-energy-consuming anabolic metabolism, retaining only minimal basal respiration and membrane transport activity [5]. Structurally, VBNC cells maintain intact cell envelopes and stable intracellular osmotic balance, which enables them to tolerate long-term oligotrophic stress that would kill normally growing cells.

Nevertheless, the VBNC survival mode carries high ecological costs that are often overlooked in short-term laboratory observations. During dormancy, intracellular metabolic enzymes, ribosomes and transport proteins undergo gradual degradation, and the transcriptional, and translational systems are substantially suppressed [5]. Although this state guarantees cell survival, it greatly weakens microbial recovery potential. Once environmental nutrients are restored, VBNC cells require a lengthy lag period to resynthesize functional proteins, rebuild metabolic networks, and reactivate cell division. This decoupling of survival ability and growth recovery ability is a core metabolic trade-off that restricts the rapid population reconstruction of heterotrophic microbes in fluctuating nutrient environments.

Furthermore, the VBNC state is not a reversible adaptive strategy without limitations. Long-term dormancy may cause irreversible damage to partial genetic and metabolic regulatory networks. A portion of cells cannot return to normal growth even after sufficient nutrient supplementation, resulting in gradual population attenuation. This indicates that heterotrophic microbial adaptation is a cost-bearing balance mechanism, and extreme stress resistance will inevitably sacrifice partial growth competitiveness.

2.3. Metabolic remodelling and endogenous energy consumption burden

To adapt to persistent nutrient starvation, heterotrophic microorganisms initiate systematic metabolic remodelling, which profoundly reshapes their substance acquisition and energy utilization patterns. Under nutrient-rich conditions, heterotrophs prioritize high-throughput substrate uptake and rapid

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glycolysis to support exponential growth. In contrast, starvation stress triggers global metabolic inhibition: cells downregulate the expression of high-affinity nutrient transporters, reduce the synthesis of non-essential amino acids and lipids, and repress energy-intensive cell cycle processes.

This adaptive metabolic transformation is energy-saving in the long run but consumes massive endogenous reserves in the short term [3]. The reconstruction of metabolic pathways requires the degradation of original functional proteins and the synthesis of stress-specific regulatory factors. These biochemical processes rely entirely on intracellular stored ATP and residual organic substances. With the continuous consumption of endogenous energy, the basal metabolic level of cells gradually decreases, and the overall physiological activity enters a continuous declining state.

Another critical metabolic adjustment of heterotrophs under stress is the enhancement of substrate scavenging spectrum. When conventional carbon sources are exhausted, E. coli can activate cryptic metabolic pathways to utilize unconventional organic substrates, including trace fatty acids, peptide fragments and residual microbial metabolites in the environment [1]. This flexible substrate utilization mechanism expands the survival threshold of heterotrophic microbes under extreme oligotrophic conditions, further reflecting their strong metabolic plasticity compared with autotrophic microorganisms.

2.4. Comprehensive advantages and inherent limitations of heterotrophic survival strategies

Heterotrophic microorganisms exhibit unique ecological advantages in complex and dynamically changing nutrient environments. Relying on flexible organic substrate utilization, intraspecific nutrient recycling, adaptive mutation and VBNC dormancy strategies, heterotrophs can efficiently cope with sudden nutrient depletion and long-term starvation stress. Their metabolic modes do not depend on specific light or inorganic environmental conditions, enabling them to widely colonize soil, water, biological tissues and various complex ecological niches [2]. Strong metabolic plasticity and stress tolerance make heterotrophs the most widely distributed microbial group in natural ecosystems [6]. However, heterotrophic survival strategies have irreparable inherent defects. The core limitation is the absolute dependence on exogenous organic nutrients. All adaptive mechanisms, including metabolic remodelling and dormant survival, can only prolong survival time but cannot fundamentally solve the problem of resource depletion. Once the external organic substances are completely exhausted and intraspecific recycling resources are consumed, heterotrophic populations will inevitably decline. Different from autotrophs with independent carbon fixation ability and mixotrophs with dual metabolic pathways, heterotrophs lack alternative energy supply routes, which means that their survival is always passively restricted by environmental resource availability. In summary, heterotrophic microbes form a set of passive but highly flexible stress adaptation systems based on exogenous substance acquisition. Their survival advantages lie in strong environmental adaptability and metabolic plasticity, while their essential weakness is the lack of autonomous resource synthesis capability, resulting in unavoidable survival bottlenecks under long-term extreme oligotrophic environments.

3. Autotrophic microorganism

Autotrophic organisms are primary producers that can synthesise complex organic molecules using inorganic carbon dioxide as their sole carbon source. They obtain energy either from sunlight or from chemical reactions of inorganic substances. Photoautotrophs such as cyanobacteria and algae rely on photosynthetic pigments to capture light energy for carbon fixation [7]. Chemoautotrophs live in light-lacking extreme habitats and gain energy from oxidising inorganic compounds. Unlike

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heterotrophs, autotrophs do not require pre-formed organic carbon from external environments. Nevertheless, photoautotrophic microbes still face survival pressure under darkness or nutrient-limiting conditions. Autotrophic microorganisms cannot directly use organic substances from outside as their nutrient sources. They need to use carbon dioxide and light energy and, through photosynthesis, synthesize their own organic substances. These types of microorganisms include cyanobacteria and photosynthetic algae.

In conditions with enough light, these autotrophic microorganisms can use light energy, carbon dioxide and water to synthesize carbohydrates, which provide the main nutrients that support their survival. If there are enough resources such as some inorganic salts, this can provide great conditions for these microorganisms to grow fast and divide at a fast rate. More importantly, excess carbon will be stored inside cells as glycogen. These types of microorganisms have specific advantages: they do not need environments full of organic substances, and they can also live in some nutrient-poor, harsh environments as long as light is available.

If there is not enough light, the pace of photosynthesis will be limited. But these microorganisms will not die quickly because they can consume the glycogen they stored during the day and maintain the lowest living activities, such as transcriptional function and substance transport across the cell membrane. However, this has a time limitation. With the over-consumption of glycogen, cellular activities will decrease. Even if light is restored afterwards, some cells cannot remain active. Another point is that different types of autotrophic microorganisms have different tolerances for dark conditions.

The core limitation of these organisms is that their survival highly depends on light. Although the environment has plenty of organic substances, these kinds of microorganisms cannot use them to continue surviving. Compared with unicellular microorganisms such as "E. coli" or some mixotrophic microorganisms, autotrophs may have fewer chances to survive. Those other groups possess a wider adaptive range. For this type of organism, their advantage is that they can survive in nutrient-lacking conditions, but their main limitation is that the lack of light will threaten their survival. This also illustrates that every survival strategy has both advantages and limitations. It is noticeable that photoautotrophs still require essential inorganic nutrients such as nitrogen and phosphorus for synthesizing proteins and nucleic acids [8]. Without these inorganic nutrients, they are unable to grow or survive over the long term. Structures such as chlorophyll-containing thylakoids also impose constant metabolic costs on cells [6]. Even under dark conditions when photosynthesis ceases, these structures still require continuous repair, which consumes energy and cellular resources. This additional resource expenditure further aggravates energy pressure when intracellular glycogen reserves are being depleted.

4. Mixotrophic microorganisms

The last type is mixotrophic microorganisms. They do not rely on a single nutritional strategy. Instead, they can utilize multiple carbon and energy resources, combining heterotrophic and autotrophic metabolic pathways. Mixotrophs exhibit diverse nutritional combinations, including light energy, chemical energy, organic nutrients, and inorganic nutrients [8]. For mixotrophic organisms, neither heterotrophy nor autotrophy can be absent.

However, these advantages do not hold under all environmental conditions. When a single resource is limiting, mixotrophy can confer adaptive benefits, but these advantages can be readily offset by the energetic burden of maintaining a dual metabolic system. Under such conditions, mixotrophic microorganisms do not exhibit a clear competitive advantage over other nutritional

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strategies. In contrast, when multiple resources are simultaneously limited, mixotrophs enjoy a greater advantage than either strict autotrophs or strict heterotrophs [9]. When one trophic pathway is constrained by a limiting resource, the alternative pathway can alleviate this limitation. For instance, when cells simultaneously suffer from inorganic-nutrient and carbon shortage, mixotrophs can combine photosynthetic carbon fixation with heterotrophic nutrient acquisition. This accounts for their competitive superiority in habitats where both nutrients and carbon are scarce.

These two trophic modes impose fundamental resource burdens on mixotrophic microorganisms. Cells need to continuously consume ATP, carbon, nitrogen and phosphorus to synthesize and repair the enzymes and structural components required to sustain cellular survival. Owing to this constant resource investment, mixotrophs may not achieve higher growth rates than strict heterotrophs or photoautotrophs under stable, resource-replete environments, as the extra metabolic overhead cannot yield corresponding fitness benefits [9, 10]. In addition, fluctuations in light intensity and resource availability can alter metabolic rates. A high metabolic rate enables cells to synthesize new functional components, and this drastic metabolic rearrangement consumes large amounts of transient energy and nutrients. Consequently, mixotrophs rarely maintain internal nutrient storage to withstand resource-limitation pressure. By comparison, alternative adaptive mechanisms avoid drastic metabolic remodeling to mitigate such risks. Therefore, the overall adaptability of mixotrophic microorganisms relies on the balance among multiple interacting factors. Meanwhile, operating two separate metabolic systems requires continuous resource input.

5. Conclusion

This paper explores different nutritional types of unicellular microorganisms, how they acquire substances, regulate energy metabolism, and face nutrient-limited environments. Heterotrophic organisms represented by E. coli rely on organic compounds from the environment and use nutrient recycling, adaptive mutation, and the VBNC dormant state to extend survival time under starvation conditions, but their survival is fundamentally affected by external organic resources. Autotrophic organisms obtain a degree of metabolic independence through inorganic compounds, and their carbon-fixing machinery requires a large amount of energy input and is easily affected by light and the shortage of inorganic nutrients. Mixotrophic organisms use both autotrophic and heterotrophic metabolic systems, broadening their metabolic range, but maintaining two pathways may have unavoidable energy consumption. For these three nutritional types, each of their adaptive behaviors can bring survival benefits and metabolic trade-offs, and no category can have absolute advantages in all kinds of environmental conditions. Through comparison and analysis, this can provide some evidence for microbial ecology and also has reference value for environmental applications such as wastewater treatment and bioremediation.

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