Review

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Review

From Extremes to Edibles: Unlocking Water Bear (Tardigrade) and Its Symbiont Potential with CRISPR for Next-Gen Superfood, Space Agriculture, Pharmaceuticals and More

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Abstract

Tardigrades, commonly known as water bears or moss piglets, are microscopic extremophiles famed for their resilience to harsh environments, including extreme temperatures, radiation, and desiccation. Beyond their unique survival traits, recent discoveries of their symbiotic microbial partners open exciting avenues for biotechnological innovation. This review explores the untapped potential of tardigrades and their symbionts as novel sources for next-generation superfoods, cosmetics and pharmaceuticals. Leveraging CRISPR gene-editing technology, we discuss strategies to enhance their nutritional profiles, stress tolerance, and metabolic pathways for sustainable food production. Integrating extremophile biology with cutting-edge genome engineering could revolutionize food systems by introducing robust, nutrient-dense, and environmentally resilient bioresources.

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Introduction

Water bears (or moss piglets), scientifically known as tardigrades, are microscopic organisms that have fascinated researchers for decades due to their extraordinary resilience to environmental extremes. These tiny creatures can survive conditions that would be fatal to most life forms, including extreme temperatures, intense radiation, desiccation, and even the vacuum of outer space (Kumagai et al., 2022). Their unique survival strategies, such as cryptobiosis (a state of suspended animation where metabolic activities nearly cease) allow them to endure prolonged periods of stress. In addition to these physical adaptations, tardigrades possess sophisticated DNA repair mechanisms that help maintain genome integrity despite exposure to damaging agents. What makes these survival feats even more remarkable is that they are not solely reliant on the tardigrade's own cellular machinery; recent studies have uncovered the vital roles played by their symbiotic microorganisms, which contribute to their stress tolerance and overall fitness (Zhang et al., 2023). Until now, the majority of research on tardigrades has focused on understanding their biology from the perspective of astrobiology, evolutionary science, and environmental stress adaptation. Their resilience has made them model organisms for studying life's boundaries, with implications for space exploration and extremophile biology. However, one promising yet underexplored avenue lies in their potential applications in food science. As global populations continue to rise and climate change threatens traditional agricultural systems, the search for alternative, sustainable, and nutrient-dense food sources has intensified. In this context, extremophiles like tardigrades, with their unique metabolic capabilities and robust nature, offer an intriguing possibility as candidates for next-generation superfoods. The exploration of tardigrades and their symbionts as novel food resources could help address pressing issues of food security, nutrition, and environmental sustainability.

The advent of CRISPR gene-editing technology has revolutionized biological research, providing scientists with precise tools to modify genomes efficiently and accurately. This breakthrough offers exciting possibilities for harnessing the unique biology of tardigrades and their microbial partners for human benefit (Zhang et al., 2023). By using CRISPR to enhance desirable traits such as nutrient production, stress tolerance, and growth efficiency, it becomes possible to tailor these extremophiles for use in food systems that can withstand harsh environmental conditions. Genetic modifications can optimize metabolic pathways to increase the synthesis of essential amino acids, vitamins, or antioxidants, making tardigrades and their symbionts not only resilient but also highly nutritious (Zhang et al., 2023). Furthermore, CRISPR-enabled manipulation of symbiotic microorganisms opens new frontiers in synthetic biology, allowing the design of customized microbial communities that support and enhance the growth and nutritional value of tardigrades (Kondo et al., 2024). These engineered symbioses can create stable, sustainable food production systems that require minimal inputs and thrive where conventional crops cannot. Such innovations could lead to the development of compact, efficient, and eco-friendly food production units suited for challenging environments, including urban vertical farms or extraterrestrial habitats (Kondo et al., 2024). This review aims to explore the untapped potential of tardigrades and their symbionts as next-generation superfoods through the lens of CRISPR technology. We will discuss their unique biological features, nutritional prospects, and the opportunities that genome editing presents for optimizing their use in sustainable food production. By bridging extremophile biology and cutting-edge genetic engineering, this review seeks to highlight a novel paradigm in food science that could help meet future nutritional demands while promoting environmental resilience and sustainability.

Overview of Tardigrade Biology and Extremophilic Traits

Tardigrades, commonly known as water bears, are microscopic, water-dwelling invertebrates renowned for their remarkable ability to withstand some of the harshest conditions on Earth. Measuring typically between 0.1 to 1.5 millimeters, these eight-legged creatures inhabit diverse environments ranging from mosses and lichens to freshwater and marine ecosystems (Nagwani et al., 2022). Their unique biology equips them with extraordinary extremophilic traits, enabling survival under extreme temperature fluctuations, high levels of radiation, intense desiccation, high pressure, and even the vacuum of outer space. Central to their resilience is the ability to enter cryptobiosis, a reversible state of suspended metabolism where tardigrades lose almost all body water and halt metabolic processes (Wilanowska et al., 2024). In this state, they can endure prolonged periods without food or moisture, reviving only when conditions improve. Molecular adaptations include the production of protective proteins such as tardigrade-specific intrinsically disordered proteins (TDPs) that stabilize cellular structures, as well as efficient DNA repair mechanisms that mitigate damage caused by environmental stressors.

Furthermore, tardigrades harbor diverse symbiotic microorganisms, which may contribute to their extremotolerance by producing bioactive compounds or aiding metabolic functions. Understanding the interplay between tardigrades and their symbionts sheds light on complex survival strategies that extend beyond the host genome (Li et al., 2024). These exceptional biological features make tardigrades not only subjects of fundamental scientific interest but also promising candidates for biotechnological applications, including the development of resilient food systems for challenging environments (Nagwani et al., 2022). The integration of CRISPR gene-editing technology opens avenues to precisely manipulate tardigrade genomes and their microbial partners to optimize traits such as growth rate, biomass yield, and nutrient composition (Wilanowska et al., 2024). For example, metabolic pathways involved in synthesizing essential amino acids, vitamins, or antioxidants could be enhanced to produce superfoods with health-promoting properties. Moreover, CRISPR could be employed to attenuate or eliminate undesired metabolic byproducts or improve stress response genes to further boost their robustness under industrial cultivation conditions.

CRISPR as a Tool for Genetic Enhancement of Tardigrades and Their Symbionts

The application of CRISPR-Cas9 technology in tardigrades offers exciting possibilities for unlocking and enhancing their biological and nutritional potential. Although gene editing in tardigrades is still in its early stages due to challenges like their tough cuticle, small size, and limited genetic tools, the fundamental CRISPR mechanisms are applicable and highly promising. The unique resistance traits such as desiccation tolerance, radiation resistance, and cryptobiosis of tardigrades and their symbionts, are controlled by specific genes like Dsup (Damage suppressor), which can be precisely studied and potentially enhanced using CRISPR (Zhang et al., 2023). By targeting these genes, CRISPR can help dissect the molecular basis of tardigrade resilience and enable synthetic enhancement of stress-tolerance traits, making them even more suitable for cultivation in extreme environments (Kumagai et al., 2022). Furthermore, CRISPR could be used to introduce metabolic pathway genes that boost protein yield, fatty acid synthesis, or the production of antioxidant compounds, tailoring tardigrade physiology for nutritional optimization (Kondo et al., 2024). Additionally, CRISPR offers the possibility to modify symbiotic microbes within tardigrades to improve mutualistic interactions or engineer them to produce essential nutrients, such as vitamins or bioactive peptides. This dual-targeting approach, editing both host and symbiont, could dramatically increase the nutritional value and functional versatility of tardigrades as a food source.

Superfood, Nutrition and Space Agriculture

Tardigrades have traditionally been studied for their remarkable resilience rather than their nutritional value. However, growing interest in sustainable and resilient superfood systems has shifted attention toward their potential as a novel, high-value superfood source. Preliminary research indicates that tardigrades may be rich in proteins, essential amino acids, and bioactive compounds beneficial to human health (Lim et al., 2024). Their survival in extreme conditions suggests they produce unique metabolites such as antioxidants, protective sugars like trehalose, and DNA-stabilizing proteins that could offer added nutritional or therapeutic benefits (Nguyen et al., 2022). With the advent of CRISPR gene-editing technology, it is now possible to enhance these nutritional traits by upregulating beneficial biosynthetic pathways or introducing new ones. CRISPR can also be used to reduce undesirable components, improve digestibility, and optimize metabolic efficiency in both tardigrades and their symbiotic microbes. This opens the door to engineering tardigrades as programmable micro-factories for producing functional superfood components, positioning them as a promising frontier in the next generation of superfoods (Lim et al., 2024). Furthermore, CRISPR-edited tardigrades for growing food in extreme extraterrestrial environments (For example, Mars missions) are being explored under the field of space agriculture.

Llorente et al. (2022) discuss the use of bioengineered microbes as versatile platforms for space nutrition. They envision genetically modified microorganisms, such as yeast, to produce essential nutrients, offering customizable food production systems with minimal inputs and waste (Llorente et al., 2022). This approach could be adapted to engineer tardigrade symbionts for similar purposes. Reysenbach and Terns (2023) explore the expanding roles of CRISPR systems beyond defense against mobile genetic elements. Their findings suggest that CRISPR systems can influence symbiotic relationships, potentially transforming parasitic associations into mutualistic ones (Reysenbach and Terns, 2023). This insight could inform strategies to engineer tardigrade symbionts for beneficial outcomes in food and agriculture. Tibbs-Cortes et al. (2022) conducted a study on tardigrade community microbiomes in North American orchards, identifying putative endosymbionts and plant pathogens. Understanding these microbial associations is crucial for potential CRISPR-based interventions aimed at enhancing food production and resilience (Tibbs-Cortes et al., 2022).

Pharmaceuticals

Tardigrades and their symbiotic microbes hold immense promise for pharmaceutical applications. CRISPR can be used to harness or enhance their natural stress-resistance genes such as Dsup, which protects DNA from damage, for potential use in human gene therapy, radiation protection, or anti-aging treatments (Kasianchuk et al., 2023). Additionally, their symbionts could be genetically modified to biosynthesize rare bioactive compounds, therapeutic enzymes, or novel antioxidants (Hashimoto et al., 2016). These engineered organisms may serve as sustainable micro-factories for next-gen biopharmaceuticals, reducing reliance on scarce natural sources and enabling cost-effective drug production (Clark-Hachtel et al., 2024).

Hashimoto et al. (2016) analyzed the complete genome sequences of one of the most stress-tolerant tardigrade species, *Ramazzottius varieornatus*, and discovered that its gene content shows a minimal presence (1.2% or less) of potential horizontally transferred genes, the absence of certain pathways typically linked to stress-induced damage, and the expansion of gene families involved in damage mitigation. Interestingly, using cultured human cells, they evidenced that a DNA-binding protein unique to tardigrades reduces X-ray-induced DNA damage by approximately 40% and enhances resistance to radiation (Hashimoto et al., 2016). These results highlight the potential role of tardigrade-specific proteins in stress tolerance and suggest that tardigrades may serve as a valuable source of novel protective genes and mechanisms (Hashimoto et al., 2016). Clark-Hachtel et al. (2024) have recently demonstrated that tardigrade *Hypsibius exemplaris* DNA repair genes aid greatly in enhancing the radiation tolerance of bacteria *in vivo*. This breakthrough supports the pharmaceutical use of CRISPR by enabling the transfer of stress-tolerant genes into microbial systems for producing resilient biofactories capable of synthesizing therapeutic compounds even under extreme conditions.

Environmental Biotechnology

Tardigrades are known for their ability to survive extreme environmental conditions, such as desiccation, radiation, and temperature extremes. This resilience is partly attributed to their symbiotic relationships with microorganisms, which may possess unique metabolic pathways and stress-response mechanisms (Li et al., 2023). Harnessing these traits through CRISPR-Cas9 genome editing could lead to the development of robust microbial strains capable of degrading environmental pollutants or withstanding toxic conditions (Palit et al., 2025). Recent advancements in CRISPR technology have enabled the precise editing of microbial genomes to enhance their capabilities in environmental remediation. For example, CRISPR-Cas9 has been used to engineer bacterial strains for improved metal detoxification and degradation of organic pollutants (Chai et al., 2025). These engineered microbes can be employed in bioremediation strategies to clean up contaminated environments. Moreover, CRISPR-based tools have facilitated the development of biosensors and microbial consortia tailored for specific environmental applications, such as wastewater treatment and pollutant monitoring. These innovations underscore the potential of CRISPR technology in enhancing the functionality of environmental microorganisms.

Li et al. (2023) have developed a synthetic biology CRISPR-Cas immunity based system named VADER that is capable of removing 100% of the targeted antibiotic resistance genes from the environment. In future, tardigrade symbionts could be engineered with VADER-like CRISPR constructs to combat antibiotic resistance in aquaculture, soil, or food production systems where resistant bacteria persist. These microbes could colonize or interact with key environments and selectively degrade resistance genes. Additionally, tardigrade symbionts could be modified using PlastiCRISPR systems to express plastic-degrading enzymes, enabling efficient biodegradation in extreme environments. Building on the work by Palit et al. (2025), these engineered microbes offer eco-friendly solutions for plastic waste management in habitats where conventional biodegraders cannot survive or function effectively. The discovery of *Pseudoxanthomonas mexicana* CH capable of degrading nonylphenol (NP, a man-made toxic from plastic manufacturing) by Chai et al. (2025) highlights the potential of environmental bacteria in pollutant removal. Similarly, tardigrade symbionts could be engineered with CRISPR to express NP-degrading pathways, leveraging their resilience in extreme environments for advanced bioremediation of persistent pollutants like NP in challenging ecosystems.

Cosmetics

Tardigrades, known for their extraordinary ability to withstand extreme environmental stressors such as desiccation, UV radiation, and even space exposure, have become an unexpected yet promising source of innovation in the cosmetics industry (Li et al., 2023). One of their most studied resilience-associated proteins is Dsup (damage suppressor), which has been shown to protect DNA from radiation-induced damage by forming a protective shield around the genetic material. In recent years, this protein has captured the interest of cosmetic researchers aiming to develop next-generation anti-aging and skin-protective products (Bhat & Garibyan, 2022). With the aid of CRISPR technology, genes encoding tardigrade-specific protective proteins like Dsup can be introduced into safe microbial platforms or cell lines used in cosmetic ingredient production. These engineered organisms can biosynthesize tardigrade proteins at scale, offering a sustainable source for bioactive ingredients with demonstrated protective properties. Alternatively, synthetic biology approaches may allow direct incorporation of Dsup or similar proteins into skincare formulations, where they could act as antioxidants, DNA protectants, or cellular stress modulators (Li et al., 2023).

Moreover, tardigrade symbionts, which often exhibit resilience traits similar to their hosts, could be explored and engineered via CRISPR to produce beneficial metabolites such as UV-absorbing compounds or bio-compatible moisturizers. These symbiotic microbes may serve as biofactories for skin-repair agents that are both effective and eco-friendly. Incorporating tardigrade-derived biomolecules into cosmetics represents a futuristic shift towards biologically intelligent skincare (Li et al., 2023). These innovations could not only slow aging at the molecular level but also provide enhanced protection for individuals exposed to high-stress environments, such as frequent flyers, outdoor workers, or astronauts (Bhat & Garibyan, 2022). As demand grows for novel, scientifically backed skincare solutions, the fusion of tardigrade biology and CRISPR engineering may lead to a new class of advanced cosmetic products with unparalleled protective benefits.

Bioenergy and Biopreservation

Tardigrades, renowned for their resilience, possess unique biological mechanisms that can be harnessed through CRISPR technology for applications in bioenergy and biopreservation. While direct studies on CRISPR-engineered tardigrade symbionts for biofuel production are currently limited, the concept draws inspiration from the broader field of extremophile biotechnology. Tardigrades host a variety of microbial symbionts, some of which may possess metabolic pathways conducive to biofuel synthesis (Nguyen et al., 2022). By applying CRISPR-Cas9 technology, these symbionts could be genetically modified to enhance the production of biofuels or high-energy compounds, especially under extreme environmental conditions. For instance, certain tardigrade-associated bacteria might be engineered to optimize lipid production, a key component in biodiesel (Zhang et al., 2023). The resilience of these microbes to desiccation and radiation, traits inherited from their tardigrade hosts, could make them ideal candidates for bioenergy applications in harsh environments, including space habitats or arid regions on Earth. Tardigrades' ability to survive extreme desiccation and radiation is largely attributed to their production of intrinsically disordered proteins (IDPs), such as cytoplasmic abundant heat soluble (CAHS) proteins. These proteins vitrify cellular components, protecting them from damage during dehydration (Lim et al., 2024).

Research led by Nguyen et al. (2022) has demonstrated that tardigrade CAHS proteins and trehalose work in a synergistic manner to enhance desiccation resistance. This discovery opens avenues for biopreservation applications, such as stabilizing vaccines and biologics without the need for refrigeration, which is particularly beneficial in remote or resource-limited settings (Nguyen et al., 2022). Furthermore, the application of these proteins could revolutionize the storage and transport of perishable goods, extending shelf-life and reducing reliance on cold-chain logistics (Nguyen et al., 2022). Such advancements are crucial for global health initiatives and long-duration space missions, where traditional refrigeration may not be feasible. On the other hand, Zhang et al. (2023) expressed tardigrade disordered proteins in cyanobacterium *Synechocystis* sp. PCC6803 (biofuel factory) to significantly improve the biofuel stress resistant and tolerance level of this species. This genetic modification significantly enhanced the strain's tolerance to environmental stresses typically associated with biofuel production, such as oxidative stress and solvent toxicity. By leveraging the protective properties of tardigrade proteins, particularly their role in stabilizing cellular structures under extreme conditions, the engineered cyanobacteria exhibited improved survival and productivity (Zhang et al., 2023). This study demonstrates a pioneering application of extremophile biology in industrial biotechnology and highlights the potential of combining CRISPR and synthetic biology to enhance microbial robustness in next-gen bioenergy systems.

Future Directions, Research Gaps and Conclusion

Advancing the use of tardigrades and their symbionts in next-generation superfood systems hinges on integrating cutting-edge technologies like multi-omics and artificial intelligence (AI). Combining genomics, transcriptomics, proteomics, and metabolomics will enable a comprehensive understanding of metabolic pathways and stress tolerance mechanisms (Jee et al., 2017; Lim et al., 2021; Lim, 2022). AI-driven data analysis can accelerate precision CRISPR editing by predicting optimal gene targets for enhanced nutrition, resilience, and safety (Lim, 2025a-b). This integrated approach promises more efficient and targeted development of engineered tardigrade-based foods, pharmaceuticals and cosmetics.

Despite promising prospects, significant research gaps remain. The nutritional profiles of many tardigrade species and their symbionts are poorly characterized, limiting our understanding of their full potential as food sources. Furthermore, robust protocols for cultivating and scaling these micro-animals under controlled conditions need development. Safety assessments, including allergenicity and toxicity, are also critical before commercial application. Ethical and regulatory frameworks for CRISPR-edited organisms in food remain evolving, demanding proactive engagement with stakeholders. Beyond tardigrades, exploring other extremophiles could uncover complementary traits such as enhanced vitamin synthesis or unique bioactive compounds, enriching superfood formulations. Multi-species CRISPR editing strategies could leverage synergistic effects to build resilient, nutrient-dense food systems adapted to climate change and resource scarcity. Market potential for CRISPR-engineered tardigrade superfoods is promising, particularly among health-conscious consumers and space agriculture initiatives. However, consumer acceptance depends on transparent communication of benefits, safety, and ethical considerations. Educating the public about the sustainable and nutritional advantages of such novel foods will be essential.

In conclusion, harnessing tardigrades and their symbionts through CRISPR offers an exciting frontier for sustainable, resilient, and nutrient-rich food innovation. Bridging existing knowledge gaps with interdisciplinary research and technology integration will be key to transforming these extremophiles from scientific curiosities into practical superfood, pharmaceuticals and space agriculture solutions for the future.

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