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THE ROLE OF EMERGING TECHNOLOGIES IN ANTI-AGING MEDICINE: FROM GUT MICROBIOME ANALYSIS TO PERSONALIZED SUPPLEMENTATION

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ABSTRACT

Aging is a complex, multifactorial biological process driven by interconnected molecular and cellular mechanisms, including genomic instability, mitochondrial dysfunction, chronic inflammation, cellular senescence, and alterations of the gut microbiome. Growing evidence from geroscience supports the concept that aging is not merely inevitable but can be modulated by targeted interventions acting on these core pathways. This review examines the role of emerging technologies in anti-aging medicine, with a particular focus on how advances in molecular profiling, gut microbiome analysis, artificial intelligence, and digital health are transforming the field toward precision-based strategies. We summarize current knowledge on key biological drivers of aging, including inflammaging, mitochondrial decline, and microbiome dysbiosis, and discuss their overlap with age-related diseases such as cancer, neurodegeneration, and metabolic disorders. Furthermore, we highlight technological innovations enabling the identification of biomarkers of biological age, development of immune and inflammatory aging clocks, and application of machine learning for personalized nutrition and supplementation. Special attention is given to individualized interventions involving dietary modulation, microbiome-targeted therapies, and bioactive compounds such as polyphenols, NAD^+ boosters, spermidine, omega-3 fatty acids, and curcumin. Finally, we explore future directions, including computational drug discovery, synthetic biology–based microbiome engineering, and programmable digital health ecosystems. Together, these advances illustrate a paradigm shift from generalized anti-aging approaches toward integrated, data-driven, and personalized strategies aimed at extending healthspan and improving resilience to age-related disease.

Materials and Methods: A structured literature review was conducted using the PubMed database as the sole source of scientific evidence. Articles published within the last five years were included to ensure the use of up-to-date data relevant to the rapidly evolving field of anti-aging medicine. The search focused on peer-reviewed original studies, systematic reviews, and high-quality narrative reviews related to aging mechanisms, gut microbiome analysis, synthetic biology, digital health, wearable technologies, artificial intelligence, precision nutrition, and personalized supplementation strategies. Studies were selected based on relevance to the topic "The Role of Emerging Technologies in Anti-Aging Medicine: From Gut Microbiome Analysis to Personalized Supplementation", scientific rigor, and translational applicability. Articles addressing molecular pathways of aging, microbiome modulation, biomarker-guided interventions, and technology-driven personalization approaches were prioritized.

KEYWORDS

Aging Biology, Anti-Aging Technologies, Aging Biomarkers, Biological Aging, Personalized Supplementation, Geroscience

CITATION

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1. Introduction

Aging is a complex biological process involving multiple interconnected molecular and cellular mechanisms that lead to progressive decline in cellular and tissue function and increased susceptibility to disease. It is associated with telomere shortening, DNA damage, mitochondrial dysfunction, declining NAD^+ levels, impaired autophagy, stem cell exhaustion, chronic inflammation, loss of proteostasis, deregulated nutrient sensing, altered intercellular communication, and gut dysbiosis (Y. Li et al., 2024). The aging process is influenced by genetic, lifestyle, and environmental factors. For many years, aging was considered inevitable, and age-related diseases were viewed as unavoidable and irreversible. However, the rapidly expanding field of geroscience has challenged this paradigm by proposing that aging is not merely a passive process but a potentially modifiable therapeutic target, although its clinical "treatment" still requires robust evidence and appropriate regulatory frameworks (DeVito et al., 2022). The geroscience hypothesis suggests that targeting fundamental mechanisms of aging may simultaneously delay multiple age-related diseases and extend healthspan. Current research explores interventions such as senolytics, NAD^+ boosters (including NR and NMN), and metformin. While preclinical studies demonstrate promising improvements in healthspan in animal models, human clinical evidence remains limited and requires long-term studies to confirm efficacy, safety, and optimal indications (Espinoza et al., 2023). Age-related biological changes may also be mitigated through lifestyle-based interventions, including caloric restriction, improved sleep, physical activity, and modulation of longevity-associated genes. These strategies act on core aging pathways such as nutrient sensing, mitochondrial function, inflammation, and autophagy. Caloric restriction and regular exercise enhance metabolic efficiency and cellular resilience, while adequate sleep supports immune balance and systemic recovery. Emerging insights into longevity-associated genes further suggest that targeted behavioral and molecular interventions may partially counteract functional decline, reinforcing a more proactive and modifiable view of aging biology (Y. Li et al., 2024)[1]. Despite decades of research and substantial academic and industrial investment, translating mechanistic insights into effective and clinically validated anti-aging therapies remains challenging. Progress has often been limited by fragmented experimental models, narrow validation strategies, and insufficient integration of complex biological networks underlying aging. Because aging results from highly interconnected molecular cascades rather than isolated pathways, therapeutic development requires systems-level approaches and rigorous study design to distinguish truly disease-modifying interventions from preliminary or overstated findings. This need for methodological robustness underscores the importance of emerging technologies capable of integrating multi-omics data, longitudinal biomarkers, and computational modeling to refine both target identification and therapeutic evaluation (Rosen & Yarmush, 2023). The multidirectional nature of current research and its encouraging findings have accelerated the development of anti-aging medicine. Advances in modern technologies now enable a deeper understanding of aging pathways and more precise intervention strategies. This review examines how emerging technologies inform personalized anti-aging approaches and summarizes recent discoveries and future directions in this evolving field.

2. Results

2.1 Biological Basis of Aging

Aging is driven by specific "hallmarks" that intensify with age, accelerate aging when experimentally enhanced, and can be therapeutically modified. These include genomic instability, telomere attrition, epigenetic alterations, loss of proteostasis, impaired autophagy, deregulated nutrient sensing, mitochondrial dysfunction, cellular senescence, stem cell exhaustion, chronic inflammation, and dysbiosis. These mechanisms are interconnected and are also linked to the "hallmarks of health," defined as the maintenance of homeostasis, proper spatial organization, and appropriate stress responses (López-Otín, Blasco, et al., 2023). Some hallmarks are shared between aging and cancer development. Mechanisms such as genomic instability, epigenetic alterations, chronic inflammation, and dysbiosis function as common "meta-hallmarks." Others, including telomere shortening and stem cell exhaustion, may exert tumor-suppressive effects. Autophagy and cellular senescence display context-dependent roles, acting as both tumor-suppressive and tumor-promoting processes. These interactions influence age-related patterns of cancer incidence and mortality, as well as oncological treatment strategies in older populations (López-Otín, Pietrocola, et al., 2023). Aging is associated with chronic, systemic, low-grade inflammation ("inflammaging"), accompanied by cellular senescence, immunosenescence, and progressive organ dysfunction. Factors secreted by senescent cells, collectively known as the senescence-associated secretory phenotype (SASP), amplify inflammation and induce senescence in surrounding cells. Persistent inflammation further weakens immune function, creating a self-reinforcing cycle of inflammation and senescence. Sustained inflammatory signaling leads to tissue damage and age-related diseases. Because inflammation is a central endogenous mechanism of aging, its modulation represents a promising anti-aging strategy (Li et al., 2023). Mitochondria also play a crucial role in aging. In addition to energy production, they possess their own DNA, and their dysfunction results in oxidative stress (excess reactive oxygen species), mitochondrial DNA damage, disrupted mitochondrial dynamics and mitophagy, and activation of inflammatory pathways. These alterations increase with age and contribute to the development of cancer, cardiovascular, neurodegenerative, and metabolic diseases. Mitochondria may therefore represent a central regulator of aging, and therapies targeting mitochondrial function are promising, although still clinically limited and requiring further research (Xu et al., 2025).

2.2 Gut Microbiome and Aging

The gut microbiome is considered a significant contributor to aging processes. The composition of the human gut microbiota changes throughout life under the influence of birth mode, diet, environment, medications, geographic location, and aging itself. Specific microbial features are associated with diseases at different life stages and may influence the quality of aging. A diverse gut microbiome in older individuals, particularly one enriched in bacteria that produce anti-inflammatory metabolites such as short-chain fatty acids (SCFAs), is consistently associated with healthy aging across populations (Bradley & Haran, 2024). Microbiome alterations are also linked to neurodegeneration, including mild cognitive impairment (MCI), dementia, Alzheimer's disease, and Parkinson's disease, and may serve as biomarkers of longevity in older adults. The gut microbiome therefore represents a potential therapeutic target for improving cognitive function and supporting healthy brain aging (Borrego-Ruiz & Borrego, 2024). Commensal microbiota support brain development, behavior, and healthy aging; thus, their modulation may hold therapeutic potential. Fecal microbiota transplantation (FMT), already effective in recurrent Clostridioides difficile infection, is emerging as a potential strategy in neurological disorders (e.g., Parkinson's disease, multiple sclerosis, Alzheimer's disease, and depression) and may also contribute to promoting healthy aging (Ahmadi et al., 2024).

2.3 Technological Advances in Anti-Aging Research

Overall, the recognition of aging as a modifiable biological process has catalyzed the transition from traditional disease-centered care toward Precision Geromedicine, which focuses on targeting fundamental aging mechanisms to extend healthspan. The growing burden of aging-related diseases highlights the urgency of this paradigm shift, particularly in rapidly aging societies. Singapore provides a compelling example of a country that, through systemic healthcare reforms, national preventive strategies, and substantial investment in geroscience research, is building an integrated framework linking early diagnostics with targeted therapeutic interventions. Its strong clinical infrastructure, digital health capacity, and policy coherence position Singapore as a potential global benchmark for implementing precision-based anti-aging strategies to address demographic aging and its associated disease burden (Amalaraj et al., 2025). Advances in molecular biology have enabled the identification of key aging mechanisms at the level of genes and cellular signaling pathways, including processes that accelerate aging (gerogenes) and those that suppress it (gerosuppressors). These mechanisms are closely associated with age-related diseases and represent promising therapeutic targets. Modern molecular profiling technologies—including genomics, epigenomics, metabolomics, and microbiomics—facilitate the identification of biomarkers of biological age, which are often more accurate than chronological age. This enables the assessment of aging trajectories and the monitoring of anti-aging interventions, including dietary modification and personalized supplementation (Kroemer et al., 2025). Best et al. (2025) demonstrated that aging is associated not only with alterations in gut microbiome composition but, more importantly, with a pronounced decline in metabolic activity and beneficial intermicrobial interactions. These disturbances lead to deregulation of critical host metabolic pathways, particularly those involved in nucleotide metabolism essential for intestinal barrier integrity, cellular replication, and homeostasis. The concurrent increase in systemic inflammation suggests that microbiome dysfunction may actively drive aging through metabolic and inflammatory mechanisms, positioning the gut microbiome as a key regulator of aging biology and a promising therapeutic target for personalized anti-aging strategies (Best et al., 2025). Bao et al. (2023) emphasized that aging biomarkers are essential tools for the objective assessment of biological age, monitoring the pace of physiological aging, and early detection of the transition from healthy aging to pathological states. A comprehensive, multilevel framework integrating physiological parameters, medical imaging, histological features, cellular alterations, molecular changes, and secretory factors enables a holistic characterization of aging processes. Effective biomarkers should be specific, reflect systemic biological changes, and demonstrate clinical relevance, thereby forming the foundation of precision medicine and personalized anti-aging interventions (Aging Biomarker Consortium et al., 2023). The identification of core aging-associated genes such as DPP9, GNAZ, and RELL2 highlights specific molecular targets amenable to therapeutic modulation. The application of machine learning approaches and Mendelian randomization strengthens the causal interpretation of these associations beyond simple correlation. Furthermore, the discovery that compounds including resveratrol, folic acid, and ethinyl estradiol can influence aging-related gene expression suggests the potential for pharmacological attenuation of degenerative processes. The role of immune cell populations as mediators further underscores the central importance of inflammation and immunoregulation in aging biology. Collectively, the findings reported by Yang et al. (2025) indicate that precise molecular targeting may underpin future anti-aging therapies integrating genomic insights with personalized pharmacological interventions (Yang et al., 2025). Recent advances in artificial intelligence and systems immunology have further enabled the development of highly sensitive aging metrics based on inflammatory and immune signatures. Deep learning analysis of large-scale immunome data has led to the creation of the inflammatory clock of aging (iAge), a biomarker that accurately reflects immunosenescence, multimorbidity, frailty, and cardiovascular aging. The identification of CXCL9 as a central driver of age-related chronic inflammation establishes a mechanistic link between immune dysregulation and organ-level aging, particularly vascular and cardiac dysfunction. Notably, experimental suppression of CXCL9 reverses endothelial senescence and arterial stiffness phenotypes, highlighting inflammation as a modifiable target in aging biology and reinforcing the role of computational approaches in advancing precision anti-aging therapeutics (Sayed et al., 2021).

2.4 Personalized Nutrition and Supplementation

Duan et al. (2022) concluded that aging is strongly modulated by environmental factors, particularly diet, which influences key biological mechanisms such as nutrient-sensing pathways, mitochondrial function, gut microbiota composition, metabolism, and immune regulation. While pharmacological anti-aging interventions have shown limited success and often raise safety concerns, dietary strategies represent a safer, more accessible, and cost-effective approach to slowing aging and preventing age-related diseases. At the same time, variability in responses to different dietary patterns and supplements highlights the absence of a universal solution and underscores the need for personalized approaches. The combined use of specific dietary regimens and targeted supplementation may produce additive or synergistic effects by acting on multiple aging-related pathways simultaneously. Nutrigenomics plays a central role in advancing such personalized strategies by linking individual genetic and molecular profiles with tailored nutritional interventions. Overall, these findings suggest that the future of effective anti-aging therapy lies in precision, diet-based interventions grounded in molecular biology rather than one-size-fits-all pharmacological solutions (Duan et al., 2022). From the perspective of personalized anti-aging nutrition and supplementation, the circadian system emerges as a central regulator linking diet, metabolism, the epigenome, and the gut microbiome. Chronodisruption driven by modern lifestyles promotes inflammation and metabolic dysfunction, accelerating aging processes, while genetic variability in clock genes strongly modifies individual responses to dietary interventions. Epigenetic plasticity further indicates that circadian mechanisms can be modulated by targeted nutritional compounds, and the bidirectional interaction between meal timing and the gut microbiome highlights the importance of chrono-nutrition for metabolic and inflammatory control. Together, these findings support a precision-based approach in which dietary patterns and supplements are tailored not only to molecular and microbial profiles but also to individual circadian biology to effectively slow aging and reduce age-related disease risk (Franzago et al., 2023). Based on the narrative review by Stojić et al. (2023), effective anti-aging strategies increasingly require personalization due to high interindividual variability in responses to dietary interventions, supplements, and pharmacological geroprotectors, as well as the risk of adverse effects. Machine learning–based diet and supplement recommendations provide a pragmatic bridge between heterogeneous evidence and individualized clinical decision-making by integrating lifestyle exposures, metabolic biomarkers, functional outcomes, and safety constraints. Such models enable patient-specific intervention packages combining dietary patterns, supplementation, dosing strategies, and monitoring protocols while also supporting rational combination therapies and early detection of unintended effects, thereby advancing precision anti-aging medicine (Stojić et al., 2023). Dietary polyphenols represent promising candidates for machine learning–driven personalization of anti-aging nutrition strategies. By influencing multiple hallmarks of aging—including oxidative stress, mitochondrial function, epigenetic regulation, inflammation, autophagy, and gut microbiome balance—their effects are multifactorial and highly individualized. Algorithmic models leveraging pathway-specific biomarkers can predict optimal polyphenol interventions for distinct biological profiles, enabling dynamic, holistic anti-aging strategies that evolve with changes in biological age and health status (Liu et al., 2024). NMN supplementation represents a promising but highly individualized anti-aging intervention aimed at restoring declining NAD^+ levels and improving mitochondrial function, metabolic health, and inflammatory balance. Machine learning frameworks can integrate metabolic and inflammatory biomarkers to identify responders and optimize dosing while ensuring safety, facilitating the translation of NMN from experimental studies into personalized clinical practice (Nadeeshani et al., 2022). Curcumin functions as a multitarget longevity compound modulating sirtuins, AMPK, NF-κB, and mTOR pathways involved in inflammation, metabolism, and cellular stress resistance. Given variability in bioavailability and molecular response, personalized algorithmic approaches can optimize curcumin supplementation by aligning dosing strategies with individual biomarker profiles, enhancing efficacy and safety within precision anti-aging nutrition (Izadi et al., 2024). Spermidine, a natural polyamine with anti-inflammatory and antioxidant properties, supports mitochondrial function, cellular regeneration, and longevity-associated pathways, with age-related declines linked to chronic inflammation and metabolic dysfunction. Personalized dietary and microbiome-informed strategies—including probiotic and prebiotic modulation—may restore polyamine balance, positioning spermidine as a key component of individualized anti-aging interventions (Yu et al., 2024). Beyond autophagy induction, spermidine exerts systemic anti-aging effects through immune regulation, mitochondrial metabolism, and gut microbiota–derived polyamine production. Targeted nutritional strategies enhancing endogenous spermidine availability may mitigate neurodegeneration and metabolic aging, reinforcing its role in precision longevity approaches (Hofer et al., 2021). Maintaining an optimal omega-6 to omega-3 PUFA ratio is critical for controlling chronic low-grade inflammation, a central mechanism of aging and age-related disease progression. Personalized fatty acid profiling can guide targeted omega-3 supplementation to modulate immune function, metabolic resilience, frailty, and mortality risk, although further clinical trials are needed to refine long-term dosing strategies (Poggioli et al., 2023).

2.5 Digital Health and Wearables in Anti-Aging

Digital health ecosystems integrating wearable sensors, mobile platforms, and artificial intelligence enable continuous monitoring of physiological signals, lifestyle behaviors, and nutritional patterns relevant to biological aging. These systems allow early detection of functional decline and dynamic personalization of anti-aging interventions through predictive analytics and real-time feedback. Such data-driven approaches support preventive care, facilitate timely behavioral adjustments, and transform fragmented health data into actionable insights for long-term healthspan optimization, shifting anti-aging medicine from episodic assessment toward continuous, precision-based management. By combining large-scale biological data with advanced computational models, these technologies also enable increasingly accurate estimation of biological age and risk stratification across populations, reinforcing their role in early intervention and personalized longevity strategies (Srour et al., 2025). Digital health tools and wearable technologies further improve accuracy and long-term adherence compared with traditional self-reported methods by integrating nutrition, physical activity, and metabolic data to deliver personalized behavioral guidance and adaptive lifestyle interventions that promote healthier aging trajectories. These platforms allow real-time feedback, habit reinforcement, and individualized goal setting, collectively enhancing user engagement and preventive health outcomes. As a result, anti-aging care is progressively shifting toward proactive, continuous, and precision-based models, although comprehensive long-term clinical validation remains necessary to confirm sustained health benefits (Theodore Armand et al., 2024). Digital applications for diet monitoring and precision nutrition represent a central component of modern anti-aging strategies by enabling automated dietary planning, continuous self-tracking, and individualized nutritional support for both individuals and healthcare professionals. Through AI-driven data analysis, these platforms enhance metabolic health management, chronic disease prevention, and scalability of personalized interventions, offering practical tools for translating precision nutrition into everyday life. Despite their promise, challenges related to data accuracy, interoperability, accessibility, and user trust continue to shape their real-world effectiveness and require ongoing technological and regulatory refinement (Abeltino et al., 2025). Artificial intelligence–driven technologies further expand the impact of wearables by enabling predictive monitoring of frailty, metabolic decline, and multimorbidity, thereby supporting earlier intervention, improved clinical decision-making, and tailored preventive strategies. When responsibly implemented alongside human clinical expertise, AI-supported digital health systems have strong potential to enhance health outcomes, support aging in place, and advance precision anti-aging medicine. However, ethical considerations, data privacy, algorithmic transparency, and equitable access remain critical challenges that must be addressed to ensure safe and inclusive deployment (Tana et al., 2025).

2.6 Ethical, Regulatory, and Practical Considerations

The rapid expansion of emerging technologies in anti-aging medicine—from advanced diagnostics and microbiome analysis to personalized supplementation—raises significant ethical, regulatory, and practical challenges. Limitations in accurately diagnosing biological aging increase the risk of overmedicalization, unproven interventions, and premature commercialization, highlighting the need for robust clinical validation and regulatory oversight. The growing market for supplements, biotechnologies, and alternative anti-aging solutions requires clear standards for safety, efficacy, and transparent health claims. Furthermore, issues related to equitable access, affordability, data privacy, and protection of sensitive biological information must be carefully addressed. As anti-aging strategies increasingly integrate digital health tools and personalized approaches, balancing innovation with evidence-based practice, ethical governance, and sustainable healthcare models will be essential to ensure responsible and equitable implementation (Ok, 2022). Digital technologies offer substantial potential for health promotion and disease prevention in aging populations, but their implementation raises important ethical, regulatory, and practical considerations. While tools such as mobile applications, wearables, and virtual reality platforms enable independent health monitoring, lifestyle optimization, and prolonged functional autonomy among older adults, evidence of consistent clinical benefit remains variable across outcomes. Challenges related to data privacy, ethical management of personal health information, unequal access to digital resources, and the digital literacy gap may exacerbate health disparities if not carefully addressed. Moreover, the predominance of affluent and technologically competent users in current research highlights the need for inclusive design and regulatory frameworks that ensure accessibility, safety, and equitable benefit across diverse aging populations (De Santis et al., 2023).

2.7 Future Directions

Bisht et al. (2024) demonstrate the value of integrating network pharmacology, molecular docking, and molecular dynamics simulations as powerful tools for identifying bioactive anti-aging compounds and elucidating their multitarget mechanisms of action, supporting a shift toward computationally guided discovery of phytochemicals that modulate central aging pathways and hub genes implicated in age-related diseases. Future research should prioritize experimental validation and clinical translation of these in silico–identified candidates while integrating systems biology and biomarker-driven approaches to enable precise, multipathway anti-aging therapies with improved safety and efficacy (Bisht et al., 2024). Future directions in anti-aging medicine increasingly point toward controlled modulation of hypoxia-related signaling as a novel therapeutic strategy to enhance longevity and healthspan. Beyond HIF-1 activation alone, research should explore how hypoxic responses integrate with nutrient-sensing pathways, mitochondrial metabolism, oxidative stress regulation, and inflammatory control to produce systemic anti-aging effects. Translational studies in mammals and humans will be essential to assess safety, long-term efficacy, and potential applications such as hypoxia conditioning, hypoxia-mimetic drugs, and personalized oxygen-based interventions (Nisar et al., 2025). In parallel, advances in synthetic biology are opening the possibility of programmable microbiome-based therapies in which genetically engineered gut microbes act as living biotherapeutics capable of dynamically regulating metabolism, inflammation, and cellular repair. Future anti-aging strategies may involve personalized microbial consortia designed to sense age-associated molecular changes and deliver protective metabolites in real time, shifting longevity interventions from external supplementation toward self-regulating biological systems that continuously support healthspan (Arnold et al., 2023). Finally, integration of advanced computational modeling, multi-omics data, and systems-level analysis will be critical to better capture the complexity of biological aging and translate mechanistic insights into targeted interventions. Development of dynamic aging models combining molecular networks, metabolic pathways, and longitudinal biomarker data may enable prediction of individual aging trajectories and therapeutic responses. Coupling these predictive frameworks with artificial intelligence and real-time biological monitoring is likely to accelerate precision geromedicine, shifting anti-aging research from descriptive biology toward proactive, mechanism-based prevention and personalized longevity optimization (Borgoni et al., 2021).

3. Discussion

The findings summarized in this review highlight a fundamental shift in anti-aging medicine from symptom-based management of age-related diseases toward mechanism-driven, precision interventions targeting the biological processes of aging itself. The identification of interconnected aging hallmarks—such as genomic instability, mitochondrial dysfunction, chronic inflammation, cellular senescence, and gut microbiome dysbiosis—provides a unifying framework through which emerging technologies can operate. Rather than addressing isolated pathologies, modern anti-aging strategies increasingly aim to modulate shared upstream drivers of functional decline, supporting the concept that extending healthspan may be achievable through targeted biological optimization. A major strength of recent advances lies in the integration of high-dimensional molecular data with artificial intelligence and systems biology approaches. Biomarkers of biological age, immune-based aging clocks, and genomic risk profiling enable more accurate assessment of aging trajectories than chronological age alone. These tools facilitate early detection of accelerated aging while providing measurable endpoints for evaluating lifestyle, nutritional, and therapeutic interventions. Machine learning frameworks further enhance this process by translating complex biological patterns into individualized recommendations, bridging the gap between experimental research and clinical application. The gut microbiome has emerged as a central modulator of aging, linking metabolism, inflammation, immune function, and neurodegeneration. Evidence associating microbiome diversity and metabolite production with healthy aging supports the development of microbiome-informed therapies, including targeted probiotics, dietary modulation, and future engineered microbial systems. However, substantial interindividual variability reinforces the necessity of personalized approaches rather than standardized microbiome interventions. Personalized nutrition and supplementation represent a particularly promising and accessible dimension of precision anti-aging medicine. Compounds such as polyphenols, NMN, curcumin, spermidine, and omega-3 fatty acids act on multiple aging-related pathways but demonstrate heterogeneous responses across individuals. Nutrigenomics and biomarker-guided algorithms offer a rational framework for optimizing these interventions while minimizing inefficacy and adverse effects. This personalization paradigm reflects a broader shift toward lifestyle-centered, lower-risk strategies as foundational components of longevity medicine. Digital health technologies and wearable systems further strengthen this precision model by enabling continuous monitoring of physiological, metabolic, and behavioral parameters relevant to aging. The transition from episodic clinical assessments to real-time, adaptive health management supports earlier intervention, improved adherence, and dynamic personalization of anti-aging strategies. When combined with predictive AI analytics, these systems may transform aging care into a proactive, prevention-oriented discipline. Despite these advances, significant challenges remain. Much of the current evidence derives from preclinical models or short-term human studies, limiting definitive conclusions regarding long-term efficacy, safety, and clinical impact. Standardization of aging biomarkers, data integration frameworks, and outcome measures remains incomplete. Ethical considerations- including data privacy, algorithmic bias, equitable access, and over-commercialization- require careful regulatory oversight.Future research should prioritize large-scale longitudinal studies integrating molecular profiling, digital health data, microbiome analysis, and personalized interventions within unified clinical frameworks. Such efforts will be essential to validate precision anti-aging strategies and to determine which combinations of technological and lifestyle-based approaches yield the most sustainable healthspan benefits. Overall, emerging technologies are rapidly redefining anti-aging medicine as a multidisciplinary, data-driven field centered on individualized biological optimization. Although translational hurdles remain, the convergence of systems biology, artificial intelligence, digital health, and personalized nutrition offers a compelling pathway toward clinically effective, preventive, and scalable longevity interventions.

4. Conclusions

This review demonstrates that aging is driven by interconnected molecular, metabolic, inflammatory, and microbiome-related mechanisms that can increasingly be monitored and modulated through emerging technologies. Rather than being a linear or isolated biological process, aging reflects complex crosstalk between genetic regulation, mitochondrial function, immune activity, cellular senescence, and host-microbiome interactions. Advances in molecular profiling, biomarker discovery, artificial intelligence, digital health platforms, and gut microbiome analysis are shifting anti-aging medicine from generalized interventions toward precision-based, personalized strategies aimed at extending healthspan rather than merely treating age-related diseases. Evidence supports the expanding role of personalized nutrition, targeted supplementation, immune and metabolic aging clocks, and continuous digital monitoring in optimizing individual aging trajectories. The integration of multi-omics datasets with machine learning algorithms enables more accurate biological age estimation and risk stratification, facilitating earlier and more individualized preventive interventions. At the same time, innovative directions—including computational drug discovery, microbiome engineering, and AI-driven preventive care—offer promising therapeutic potential but remain largely in early translational stages. A major limitation of current research is the scarcity of long-term human clinical trials and standardized biomarkers capable of reliably predicting intervention outcomes across diverse populations. Many proposed strategies are supported primarily by preclinical data or short-term studies, limiting conclusions regarding durability and safety. Future studies should prioritize large-scale, longitudinal, and integrative approaches that combine clinical, molecular, and digital data streams to validate safety, efficacy, and personalization frameworks. Overall, emerging technologies hold substantial promise for transforming anti-aging medicine into a proactive, data-driven, and individualized discipline; however, rigorous clinical evidence will be essential to support widespread and ethically responsible implementation.

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