

Digital technologies in life sciences: advances and opportunities*

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Digital advances are fundamentally reshaping the life sciences, with emerging technologies redefining research, diagnostics, agriculture, and biotechnology. This review provides an integrated overview of the key digital innovations shaping the field, including artificial intelligence and

machine learning, Internet of Things-based sensing, blockchain, bioinformatics, big data analytics, digital twins, robotics, and social media-driven digital communication. These tools are examined across animal science, medical science, and biotechnology to enable precision agriculture, intelligent disease diagnosis, omics-based discovery, laboratory automation, and continuous real-time monitoring. Through the analysis of recent case studies, it is demonstrated how the combination of sensing, computation, and automation is driving more predictive, efficient, and data-centered life science systems. The review also addresses major challenges related to data governance, interoperability, ethics, and implementation. To identify relevant literature, a structured search was conducted across PubMed, Web of Science, Scopus, and Google Scholar, covering peer-reviewed publications from 2014 to 2026, with emphasis on articles published from 2020 onward. Search terms combined technology-specific concepts (e.g., artificial intelligence, Internet of Things, blockchain, bioinformatics, digital twin, and robotics) with life science application domains (e.g., animal science, medical science, biotechnology, precision livestock farming, and drug discovery). Studies were included if they reported primary findings, systematic reviews, or substantive conceptual analyses relevant to the application of digital technologies in life sciences; non-peer-reviewed sources were incorporated only when they represented major policy or institutional reports. Overall, this synthesis highlights both the transformative potential and the practical constraints of digital technologies in life sciences, offering a forward-looking perspective on the next generation of innovation in biologically informed digital systems.

KEYWORDS: digital transformation / artificial intelligence / internet of things / big data / life sciences

Introduction

The life sciences are undergoing a major digital transformation driven by rapid progress in computing, data generation, connectivity, and analytical capacity. Across fields such as medicine, animal science, and biotechnology, digital tools are increasingly being used to collect complex datasets, support interpretation, automate workflows, and improve decision-making processes [Atanasov 2023, Yeung *et al.* 2024, Litvinova *et al.* 2025]. These developments are shifting digital technologies from supporting roles to central components of innovation in life science research and practice [Yeung *et al.* 2024]. Life science innovation also continues to span biologically rich areas such as medicinal plant and natural product research, which remain important translational domains within the broader field [Matin *et al.* 2025].

This transition is evident across multiple domains. In biomedical research and clinical care, artificial intelligence (AI) has increasingly been used to support pharmacogenomics, personalized medicine, and data-driven clinical interpretation [Xu *et al.* 2024, Fahim *et al.* 2025, Jakka *et al.* 2025, Zack *et al.* 2025]. For example, a very important leap forward in oncology has been the development of MRI-guided radiation therapy [Mutic *et al.* 2014]. In agriculture and animal science, Internet of Things (IoT)-based systems and sensor-enabled platforms support real-time monitoring of livestock, environmental conditions, and management practices, thereby strengthening precision farming approaches [Terence *et al.* 2024, Zhao *et al.* 2026]. In parallel, digitally integrated laboratory workflows and automation systems are improving experimental reproducibility, throughput, and operational efficiency in research settings [Angelopoulos *et al.* 2024].

Digital transformation in the life sciences is not confined to data analysis and automation. Social media and professional digital platforms have also emerged as relevant tools for scientific communication, public engagement, and professional networking. Recent studies of hashtag-based activity on LinkedIn and X (previously known as Twitter) have shown that these platforms can promote knowledge exchange, increase visibility of health-related initiatives, and support broader dissemination of digital health and patient safety discussions [Kletecka-Pulker *et al.* 2021, Mondal *et al.* 2022, Hribersek *et al.* 2023, Chandragiri *et al.* 2025, Singla *et al.* 2025]. These observations highlight that digital technologies are also reshaping how scientific communities interact, how information circulates, and how public and professional engagement occurs in contemporary life science ecosystems [Chandragiri *et al.* 2025, Litvinova *et al.* 2025]. Despite rapid technological progress, there is limited integrative understanding of how diverse digital tools collectively reshape life science systems.

Several recent reviews have examined subsets of digital technology adoption in the life sciences. For example, Yeung *et al.* addressed broad digital transformation in biomedical research, while Menezes *et al.* focused specifically on AI applications in precision livestock farming, and Shaikh *et al.* reviewed blockchain implementations in healthcare [Yeung *et al.* 2024, Menezes *et al.* 2025, Shaikh *et al.* 2025]. While these contributions are valuable, they are largely domain-specific or technology-specific, and do not provide an integrative cross-domain synthesis that spans animal science, medical science, and biotechnology simultaneously. Importantly, no recent review has systematically examined how multiple digital technologies such as AI, IoT, blockchain, bioinformatics, digital twins, robotics, and digital communication platforms converge and interact as a collective ecosystem across these three life science domains. This gap is significant because the transformative potential of digital technologies increasingly arises from their convergence and co-deployment rather than from any single tool in isolation.

This review addresses that gap by providing a structured, cross-domain synthesis of seven core digital technologies and their integrated roles across animal science, medical science, and biotechnology. Our primary analytical focus is on technological integration: how these tools function together, complement one another, and collectively reshape life science research and practice. We also examine key challenges to adoption and highlight forward-looking opportunities at the intersection of biology and digital innovation. By taking this integrative, multi-technology, and multi-domain perspective, this review offers a broader and more unified framework than is available in existing literature.

Literature search strategy

To identify relevant literature, a structured search was conducted across PubMed, Web of Science, Scopus, and Google Scholar, covering peer-reviewed publications from 2014 to 2026, with emphasis on articles published from 2020 onward. Search

terms combined technology-specific concepts (e.g., artificial intelligence, Internet of Things, blockchain, bioinformatics, digital twin, robotics) with life science application domains (e.g., animal science, medical science, biotechnology, precision livestock farming, drug discovery). Studies were included if they reported primary findings, systematic reviews, or substantive conceptual analyses relevant to the application of digital technologies in life sciences; non-peer-reviewed sources were incorporated only when they represented major policy or institutional reports. Overall, this synthesis highlights both the transformative potential and the practical constraints of digital technologies in life sciences, offering a forward-looking perspective on the next generation of innovation in biologically informed digital systems.

Artificial intelligence and machine learning in life sciences

Artificial intelligence (AI) and machine learning (ML) have become central drivers of digital transformation in the life sciences. Rather than functioning as isolated computational tools, they now support data interpretation, pattern recognition, prediction, and decision support across biomedical research, healthcare, agriculture, and biotechnology [Xu *et al.* 2024]. Their growing importance is closely linked to the increasing availability of large, complex datasets, including imaging repositories, genomic profiles, electronic health records, and sensor-derived measurements, which are well suited to algorithmic analysis [Swinckels *et al.* 2024, Yeung *et al.* 2024, Jakka *et al.* 2025].

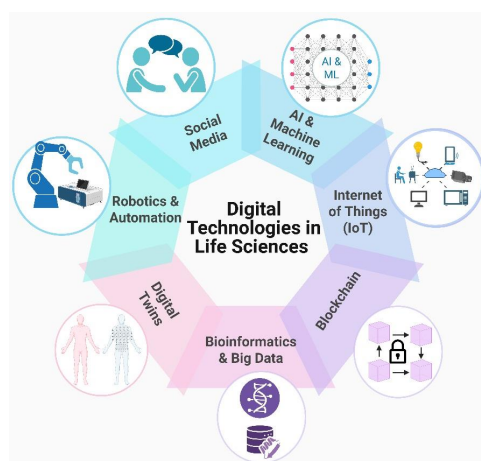


Fig. 1. Digital technologies in life sciences: an integrated conceptual framework This figure presents an integrated conceptual framework of key digital technologies in life sciences, including artificial intelligence, Internet of Things, blockchain, bioinformatics, digital twins, robotics, and social media. These technologies collectively enable data generation, processing, and application across domains such as healthcare, agriculture, and biotechnology. Interactions among technologies highlight data flow, system integration, and feedback mechanisms driving innovation, while also reflecting emerging challenges and future opportunities.

In animal science and agriculture, AI is strengthening precision livestock farming by enabling automated, non-contact, and high-throughput assessment of animals and production environments [Sztandarski *et al.* 2025]. Recent reviews have shown that computer vision systems using two-dimensional, three-dimensional, and thermal cameras can support animal identification, behavior monitoring, feed-intake estimation, body-weight prediction, and detection of health-related conditions such as lameness and heat stress [Guarnido-Lopez *et al.* 2024, Rajagukguk *et al.* 2025]. These capabilities are valuable because they reduce reliance on labor-intensive manual observation and allow more continuous, data-driven herd management. Emerging work has also suggested that natural language processing (NLP) and large language models (LLMs) may help synthesize agricultural literature and support knowledge retrieval, although their practical use in livestock systems remains at an early stage [Menezes *et al.* 2024].

The growing adoption of AI in agriculture is also reflected in institutional investment and national research programs. Public-funded initiatives in countries such as the United States have supported AI-driven research institutes and sensor-based management technologies aimed at improving animal health, nutrition, welfare, and farm automation [Menezes *et al.* 2024]. These developments indicate that AI in agriculture is moving beyond proof-of-concept studies and toward more operational and real-time systems that connect sensing, analytics, and management decisions [Guarnido-Lopez *et al.* 2024, Terence *et al.* 2024].

In medical science, AI is increasingly used for diagnostics, prognostics, and clinical decision support, as well as in neurorehabilitation, where digital monitoring tools and adaptive algorithms can help tailor rehabilitation protocols, track treatment adherence, and optimize therapeutic strategies according to individual patient needs [Park *et al.* 2025]. One of the most mature application areas is medical imaging, where deep learning systems have shown strong performance in detecting abnormalities in radiological examinations. In breast cancer screening, prospective and real-world studies have reported that AI-supported mammography workflows can maintain or improve cancer detection while reducing screen-reading workload, although the magnitude of benefit depends on the workflow design and implementation context [Lång *et al.* 2023]. These findings illustrate how AI is being integrated not simply as an experimental classifier, but as a practical support system within population-scale screening pathways [Eisemann *et al.* 2025].

Beyond imaging, ML models are increasingly being applied to longitudinal electronic health records to support earlier disease detection, risk stratification, and preventive care. According to a study by the World Intellectual Property Organization, machine learning is the dominant AI technique disclosed in patents, being included in more than one-third of all identified inventions [WIPO 2019]. Recent reviews have concluded that ML applied to EHR (Electronic Health Record) data can generate clinically useful insights across multiple disease areas, although success depends heavily on data quality, validation strategy, and interpretability [Swinckels *et al.* 2024]. AI is also playing an expanding role in pharmacogenomics and personalized

medicine by helping identify clinically relevant variants, predict drug response, and integrate multi-omics information into more individualized therapeutic strategies [Jakka *et al.* 2025]. These applications are especially promising because they move AI closer to precision medicine, where treatment selection can be guided by the combined interpretation of genomic and clinical data [Jakka *et al.* 2025].

AI is also reshaping drug discovery and biotechnology research. Computational models can prioritize compounds, predict target interactions, and assist with virtual screening, thereby accelerating the early phases of therapeutic development and reducing development costs [Mathur *et al.* 2024]. Related *in silico* approaches, including molecular docking and computational assessment of drug-likeness, pharmacokinetics, and toxicity, are increasingly used to refine candidate selection before labor-intensive experimental testing [Rajini Kanth *et al.* 2021, Mathur *et al.* 2024, Dubey *et al.* 2025]. Importantly, a 2024 analysis of AI-discovered molecules reported that, by December 2023, 24 AI-discovered drug candidates had completed Phase I trials and 21 had succeeded, suggesting an early Phase I success rate of roughly 80-90%; however, the same study was careful to note that later-stage evidence remains limited and that these findings should be interpreted as encouraging but still preliminary [Jayatunga *et al.* 2024].

Taken together, these examples show that the value of AI and ML in life sciences lies not only in automation, but in their ability to derive actionable insights from complex, heterogeneous, and rapidly expanding datasets [Xu *et al.* 2024, Litvinova *et al.* 2025]. Their impact is already visible in livestock monitoring, screening radiology, predictive healthcare, pharmacogenomics, and drug discovery. At the same time, several barriers continue to limit broader implementation, including bias in training datasets, limited transparency of complex models, challenges in external validation, infrastructure demands, and ethical concerns surrounding privacy and fairness [Jakka *et al.* 2025, Swinckels *et al.* 2024]. As data ecosystems continue to expand, the long-term influence of AI in life sciences will depend not only on algorithmic performance, but also on responsible deployment, interpretability, and integration into real-world scientific and clinical workflows [Yeung *et al.* 2024, Jakka *et al.* 2025].

Internet of things (IoT) and smart sensor networks

The IoT refers to interconnected physical devices equipped with sensors, communication modules, and computing capability that enable continuous data collection, transmission, and analysis. In the life sciences, these systems are increasingly important because they support monitoring beyond isolated time-point measurements and allow biological, environmental, and clinical processes to be followed more continuously. In healthcare, this framework is commonly described as the Internet of Medical Things, which includes connected medical devices, wearable sensors, and remote monitoring systems linked through digital infrastructure [Al Khatib *et al.* 2024].

In agriculture and animal science, IoT is a core component of precision livestock farming. Sensor systems can monitor environmental variables and animal-level parameters relevant to health, welfare, and management, while connected platforms support more continuous herd oversight and earlier detection of emerging problems [Terence *et al.* 2024]. In dairy and cattle systems, recent reviews indicate that the main value of these tools lies not simply in collecting more data, but in integrating sensor outputs into management decisions that improve monitoring efficiency and support earlier intervention [Guarnido-Lopez *et al.* 2024, Menezes *et al.* 2024].

IoT in livestock systems increasingly overlaps with AI, computer vision, and predictive analytics. Contemporary digital livestock platforms may combine wearable sensors, environmental monitoring, and image-based analysis to support more connected and decision-oriented management of animal health, productivity, and welfare [Menezes *et al.* 2024, Terence *et al.* 2024]. Because of this convergence, it is safer to describe IoT as part of an integrated digital management system rather than as a stand-alone technology [Menezes *et al.* 2024].

In healthcare, IoT-enabled systems support remote patient monitoring by allowing physiological and behavioral data to be collected outside conventional clinical settings. A recent systematic review found that remote patient monitoring interventions showed positive effects on patient safety and adherence, improved mobility and functional status in some settings, and were associated with downward trends in hospital admission, readmission, length of stay, and several cost-related outcomes, although effects on many other clinical and quality-of-life (QoL) endpoints remained inconclusive [Tan *et al.* 2024].

Despite its promise, IoT adoption across life science domains still faces major challenges. In healthcare, major concerns include privacy, cybersecurity, device reliability, and integration with existing health information systems [Al Khatib *et al.* 2024]. In animal and farm systems, recurring barriers include interoperability, scalability, data integration, and implementation complexity across heterogeneous devices and platforms [Terence *et al.* 2024]. As IoT continues to converge with AI and related analytics, its role in life sciences will likely continue to expand, but adoption will depend on how well these technical and governance challenges are addressed [Al Khatib *et al.* 2024, Terence *et al.* 2024].

Blockchain technology for data management and security

Blockchain is an emerging digital technology with increasing relevance in the life sciences, especially in areas where data integrity, traceability, transparency, and trust across multiple stakeholders are important. At its core, blockchain is a distributed ledger in which records are stored across multiple nodes and linked cryptographically in a way that makes later tampering difficult. Because of these features, blockchain has attracted interest well beyond cryptocurrencies, particularly in healthcare, biomedical research, and agri-food systems, where data often move across organizational

boundaries and where auditability and provenance are highly valued [Arif *et al.* 2024, Kasyapa *et al.* 2024, Zhou *et al.* 2024, Shaikh *et al.* 2025]. In life science settings, however, blockchain is best viewed as a specialized infrastructure for selected trust and traceability problems rather than as a universal replacement for conventional databases [Arif *et al.* 2024, Kasyapa and Vanmathi 2024, Shaikh *et al.* 2025].

One of the strongest application areas is the pharmaceutical and biomedical supply chain. In these settings, blockchain can support track-and-trace systems by creating a shared, time-stamped, and tamper-evident record across manufacturers, distributors, pharmacies, and healthcare organizations. Recent publications describe this as a promising approach for product authentication, custody verification, recall management, and counterfeit reduction, particularly because fragmented record systems often weaken transparency and slow response efforts [Ghadge *et al.* 2023, Akram *et al.* 2024, Shaikh *et al.* 2025]. Published implementation work has also shown that blockchain-based drug-tracing architectures are technically feasible in last-mile pharmaceutical workflows, supporting auditable verification and transaction visibility [Huang *et al.* 2023]. Overall, the literature suggests that pharmaceutical supply chains remain one of the clearest blockchain use cases because they align closely with the technology's strengths in provenance tracking, decentralized record keeping, and tamper-resistant logging [Ghadge *et al.* 2023, Akram *et al.* 2024, Shaikh *et al.* 2025].

Blockchain has also been explored extensively for healthcare data management, particularly for interoperable health data exchange, patient-controlled access, consent management, and audit trails. Recent reviews published in 2024 and 2025 repeatedly identify personal health records, cross-institution data sharing, access logging, and smart-contract-based permission management as common healthcare use cases [Kasyapa and Vanmathi 2024, Zhou *et al.* 2024, Shaikh *et al.* 2025]. At the same time, the evidence remains mixed. A physician-focused rapid review concluded that real-world clinical evidence is still limited and that much of the literature remains centered on conceptual frameworks and pilot architectures rather than standardized outcomes from routine deployment [Arif *et al.* 2024]. Similarly, a recent systematic review found that many blockchain healthcare implementations remain proofs-of-concept or limited-scale studies, indicating that broader adoption will require better benchmarking, stronger integration pathways, privacy-preserving designs, and clearer governance structures [Shaikh *et al.* 2025].

In biomedical research, blockchain has been proposed as a tool for strengthening data provenance, timestamping, workflow transparency, and consent tracking. These features are particularly relevant in multicenter research, biospecimen governance, clinical data sharing, and clinical trial documentation, where immutable logs may help preserve records of access, workflow steps, and protocol-related events [Kasyapa and Vanmathi 2024, Zhou *et al.* 2024]. Clinical trials are frequently discussed because blockchain-based smart contracts can theoretically record enrollment events, permissions, and selected workflow actions in a form that is resistant to retrospective alteration. A proof-of-concept study published in “JMIR Medical Informatics”

demonstrated the technical feasibility of using blockchain to manage clinical trial data, but this should still be interpreted as early translational work rather than mature routine infrastructure [Maslove *et al.* 2018]. Therefore, the strictest conclusion is that blockchain offers useful concepts for research governance and auditability, but its real-world impact in biomedical research is still emerging and remains more promising than settled [Arif *et al.* 2024, Shaikh *et al.* 2025].

Outside medicine, blockchain has become a major topic in agriculture and food systems, especially for traceability, provenance verification, transparency, and food safety. Recent systematic reviews show that blockchain-based frameworks in food supply chains are most commonly linked to traceability, transparency, tracking, monitoring, auditability, and fraud reduction [Ellahi *et al.* 2024, Pakseresht *et al.* 2024]. In agri-food systems, blockchain is often presented as a way to connect records from farms, processors, distributors, retailers, and consumers into a more unified chain of custody. This is especially attractive in sectors where provenance claims, contamination tracing, certification, or animal-product authenticity are important. Reviews focused on food and meat traceability also note that blockchain can complement other tools such as RFID (Radio-Frequency Identification), IoT sensors, and product-authenticity testing, thereby supporting more robust verification systems rather than functioning as a stand-alone solution [Ellahi *et al.* 2024, Pakseresht *et al.* 2024]. For animal agriculture specifically, the safest statement is that blockchain has potential for livestock traceability, welfare-related record keeping, and product-history verification, rather than that it is already routine practice across the sector [Pakseresht *et al.* 2024, Vern *et al.* 2025].

Despite these opportunities, blockchain still faces major technical and organizational barriers in life science applications. Commonly cited challenges include scalability, latency, storage overhead, interoperability with legacy systems, privacy concerns, regulatory uncertainty, governance complexity, and the problem of deciding what data should remain off-chain versus on-chain [Kasyapa and Vanmathi 2024, Pakseresht *et al.* 2024, Shaikh *et al.* 2025]. These limitations are especially important in healthcare, where sensitive personal data are heavily regulated, and in high-volume environments, where writing raw data directly to a blockchain may be impractical. As a result, many proposed architectures rely on hybrid models in which the blockchain stores proofs, permissions, or hashes, while larger or more sensitive data remain in secure off-chain systems [Kasyapa and Vanmathi 2024, Shaikh *et al.* 2025]. Overall, blockchain should be described as a promising but selective technology in the life sciences: it is well suited to traceability and auditability problems, but current evidence does not support presenting it as a universal backbone for all biological or clinical data systems [Arif *et al.* 2024, Shaikh *et al.* 2025].

Bioinformatics and big data analytics

Modern life sciences generate data at a scale that would have been unmanageable only a few decades ago. High-throughput sequencing, transcriptomics, proteomics, metabolomics, imaging, electronic health records, and sensor-based monitoring now produce large, heterogeneous datasets that require substantial computational infrastructure and specialized analytical methods. Bioinformatics has therefore become central to modern life science research, providing the algorithms, software, databases, and statistical frameworks needed to organize, analyze, and interpret these data [Clark *et al.* 2024, Mani *et al.* 2025, Zhang 2026]. In this context, big data analytics in the life sciences is not simply about handling large volumes of information, but about extracting biologically and clinically meaningful patterns that can improve discovery, diagnosis, and intervention [Mani *et al.* 2025].

Genomics is one of the clearest examples of this shift. The widespread use of next-generation sequencing (NGS) has transformed biology from a discipline often focused on individual genes into one capable of interrogating entire genomes, transcriptomes, and populations at once. Bioinformatics tools are essential for sequence alignment, variant calling, gene annotation, and comparative analysis across cohorts, species, and experimental platforms [Clark and Lillard 2024, Zhao *et al.* 2026]. Large-scale genomic studies, including genome-wide association studies (GWAS), now routinely analyze cohorts numbering in the hundreds of thousands or even more than one million individuals, illustrating how deeply biological discovery now depends on scalable computation and robust analytical pipelines [Keaton *et al.* 2024, Zheng *et al.* 2024]. These developments have also strengthened precision medicine efforts by enabling researchers to connect genetic variation with disease risk, prognosis, and treatment response at population scale [Mani *et al.* 2025, Mendez *et al.* 2025].

The same data-intensive logic extends beyond genomics into multi-omics and systems biology. Increasingly, researchers profile multiple molecular layers from the same biological system, including DNA sequence, gene expression, protein abundance, metabolite levels, and epigenetic state, in order to build a more integrated understanding of biological function and disease. Recent reviews emphasize that multi-omics integration can reveal disease mechanisms, improve molecular subtyping, identify biomarkers, and support more informative predictive models than single-omics analysis alone [Baião *et al.* 2025, Mani *et al.* 2025]. At the same time, these approaches also introduce major analytical challenges, including batch effects, missingness, unequal sample sizes across data types, and the difficulty of integrating information collected across different platforms and experimental conditions [Garg *et al.* 2024, Baião *et al.* 2025]. As a result, big data analytics in life sciences increasingly depends on methods that can integrate heterogeneous data while preserving biological interpretability [Toussaint *et al.* 2023, Baião *et al.* 2025].

While functional validation of multi-omics networks frequently culminates in metabolomics because of its capacity for high-resolution physiological readouts, the challenge of molecular identification remains a significant bottleneck in systems

biology. The management of these big data requires robust computational frameworks, which standardize heterogeneous raw datasets across diverse analytical instruments. The true innovation in this field lies in the transition from data accumulation to informed decision-making for molecule discovery. Platforms like MZmine integrated with SIRIUS utilize machine learning to perform de novo structure elucidation [Schmid *et al.* 2023], while the Global Natural Products Social Molecular Networking (GNPS) a web-based mass spectrometry ecosystem has revolutionized the field by transforming individual research into a global collective effort [Wang *et al.* 2016]. By leveraging crowdsourced MS/MS libraries and standardized metadata, researchers can perform automated dereplication (the rapid identification of known compounds) allowing them to focus resources on truly novel chemistry. This networked approach to big data bridges the gap between different analytical platforms, enabling scientists to prioritize the isolation of new bioactive compounds or rare biomarkers. Identifying such markers is crucial in clinical settings, as they provide essential insights into disease mechanisms, facilitate early diagnosis, and enable the monitoring of therapeutic responses. By leveraging statistical uniqueness across worldwide repositories, researchers can now more effectively pinpoint specific molecular signatures that define pathological states.

Public data repositories are another major foundation of the big data era in life sciences. Large community resources such as GenBank, GEO, and ProteomeXchange have made sequence, functional genomics, and proteomics datasets broadly accessible, allowing researchers not only to deposit data but also to reuse existing studies for secondary analyses, benchmarking, and meta-analysis [Clough *et al.* 2024, Perez-Riverol *et al.* 2024, Sayers *et al.* 2024]. These repositories have become essential to modern bioinformatics because they support data discoverability, long-term preservation, and cross-study comparison at scale [Rigden *et al.* 2024, Sayers *et al.* 2024]. The increasing reuse of public datasets has become a major driver of discovery, especially when new computational methods are applied to previously generated data or when large datasets are combined to address questions that would be underpowered in smaller studies [Clough *et al.* 2024, Perez-Riverol *et al.* 2024].

Cloud computing has also become increasingly important for bioinformatics and big data analysis. Because life science datasets are often too large or too collaborative for local analysis alone, cloud-based workflows allow researchers to store, access, and process data in distributed environments that can scale computational resources up or down as needed. This is especially useful for multinational consortia, large sequencing projects, and analysis pipelines that must be shared reproducibly across teams [Bradford *et al.* 2025, Zhang 2026]. Cloud infrastructure does not eliminate the need for careful computational design, but it does make it easier to democratize access to high-performance analysis, particularly for groups that lack local infrastructure [Bradford *et al.* 2025].

Despite these advances, major challenges remain. Biological big data are often heterogeneous, incomplete, and generated with different protocols, making harmonization and quality control essential before meaningful downstream analysis

can occur [Clark and Lillard 2024, Baião *et al.* 2025]. Human health data add another layer of difficulty because privacy, consent, and regulatory compliance must be preserved when linking molecular data with clinical information [Mendez *et al.* 2025]. There is also a persistent workforce challenge: extracting value from life science big data requires interdisciplinary expertise spanning biology, statistics, computing, and domain-specific interpretation, and many teams still face skills gaps in these areas [Jamialahmadi *et al.* 2024, Zhang 2026]. Thus, the bottleneck in big data biology is often not data generation itself, but the ability to curate, integrate, and interpret data responsibly and reproducibly [Clark and Lillard 2024, Baião *et al.* 2025].

The opportunities, however, remain substantial. Large-scale genomic sharing during the COVID-19 pandemic illustrated how public data infrastructures can accelerate surveillance and downstream scientific response [Feng *et al.* 2024]. In ecology, environmental DNA sequencing has expanded biodiversity monitoring by allowing species detection from environmental samples without direct observation [Lynggaard *et al.* 2022, Allen *et al.* 2024]. In structural biology, deep-learning systems such as AlphaFold have demonstrated how large-scale biological data and advanced computation can transform a longstanding scientific problem, making highly accurate protein-structure prediction broadly accessible and enabling proteome-scale structural resources [Jumper *et al.* 2021, Tunyasuvunakool *et al.* 2021]. Overall, bioinformatics and big data analytics now function as a core analytical layer of the life sciences, linking large-scale biological measurement to discovery, mechanism, and application across animal and human health [Mani *et al.* 2025, Zhang 2026].

Digital twins in life sciences

A digital twin is generally understood as a virtual representation of a physical entity or system that is designed to reflect relevant characteristics of its real-world counterpart and to support simulation, prediction, or decision-making. Although the concept originated in engineering, it has increasingly been adapted for healthcare and life science applications, where the target system may be a patient, organ, tissue, cell population, or broader biological environment [Drummond *et al.* 2024, Ringeval *et al.* 2025, Tudor *et al.* 2025]. In medicine, however, the term is still used inconsistently. A recent scoping review noted that many studies labeled as digital twins do not yet satisfy the strongest version of the concept, namely a personalized, dynamically updated, predictive model that informs real clinical decisions [Drummond and Gonsard 2024]. For that reason, the safest interpretation is that digital twins in life sciences currently represent a spectrum of computational models, ranging from advanced patient-specific simulations to more ambitious real-time adaptive systems that are still emerging [Ringeval *et al.* 2025, Tudor *et al.* 2025].

In healthcare, the idea of a human digital twin is closely tied to precision medicine. The goal is to integrate patient-specific data, potentially including imaging, physiological measurements, clinical history, laboratory values, genomics, and

behavioral or environmental information, into a computational model that can be used to simulate disease progression or test likely responses to different interventions [Drummond and Gonsard 2024, Tudor *et al.* 2025]. Recent reviews emphasize that this vision is attractive because it could support more individualized prevention, diagnosis, and treatment, but they also stress that most current systems remain partial implementations rather than comprehensive virtual replicas of an entire person [Rigden and Fernández 2024, Khoshfekar Rudsari *et al.* 2025]. Thus, digital twins should not yet be described as routine clinical tools across medicine; instead, they are better understood as a rapidly developing framework for computationally guided personalized care [Ringeval *et al.* 2025, Tudor *et al.* 2025].

Cardiovascular medicine is one of the most mature areas for digital twin development, as the heart was the first organ to be precisely simulated using this approach. Recent reviews in high-impact cardiovascular journals describe how patient-specific cardiac digital twins can combine anatomical imaging, electrophysiology, hemodynamics, and other personalized data to support risk prediction, procedural planning, and treatment optimization [Sel *et al.* 2024, Thangaraj *et al.* 2024]. These models are especially promising in areas such as arrhythmia modeling, structural heart interventions, and broader cardiovascular risk assessment because the heart is both highly measurable and highly modelable relative to many other organs [Sel *et al.* 2024, Thangaraj *et al.* 2024]. Even so, the literature remains careful: most applications are still being evaluated in research or early translational settings, and broader clinical adoption will require standardized validation, reproducibility, and clearer demonstrations of added value over existing decision-support tools [Sel *et al.* 2024, Thangaraj *et al.* 2024].

Digital twins are also receiving growing attention in oncology and other complex disease areas because they offer a framework for integrating multi-omics, imaging, and clinical data into more dynamic models of disease. Recent reviews describe cancer digital twins as a promising route toward patient-specific prediction of tumor behavior, treatment response, and resistance mechanisms, especially in precision oncology where static biomarkers often fail to capture tumor heterogeneity [Kemkar *et al.* 2024, Giansanti *et al.* 2025]. However, the same reviews also make clear that oncology digital twins remain scientifically and technically challenging. Tumors evolve over time, respond variably to therapy, and are influenced by multiscale biological processes that are difficult to measure continuously in real patients [Kemkar *et al.* 2024, Giansanti and Morelli 2025]. Therefore, it is safer to say that digital twins in oncology are promising computational frameworks under active development, rather than established clinical systems that can already select the best therapy for most patients [Kemkar *et al.* 2024].

The practical operation of digital twins depends on the convergence of several digital technologies. Continuous or repeated data acquisition may come from imaging platforms, monitoring devices, wearables, laboratory testing, and electronic health records, while artificial intelligence and mechanistic modeling are used to

update the virtual model and generate predictions [Rigden and Fernández 2024, Khoshfekar Rudsari *et al.* 2025]. This makes digital twins less a single technology than an integrative framework built on data pipelines, model updating, and predictive simulation. Reviews repeatedly note that the usefulness of a digital twin depends not only on modeling sophistication but also on the quality, frequency, interoperability, and clinical relevance of the incoming data streams [Drummond and Gonsard 2024, Khoshfekar Rudsari *et al.* 2025]. In other words, a digital twin is only as informative as the biological assumptions and data infrastructure that sustain it [Ringeval *et al.* 2025].

Another promising area is critical care and acute care medicine, where rapidly changing physiology makes dynamic modeling especially attractive. A 2025 narrative review described digital twins in critical care as potentially useful for medical education, *in silico* experimentation, and clinical decision support by integrating streams of patient monitoring data into predictive models of deterioration and response [Halpern *et al.* 2025]. Yet the same literature remains cautious. Intensive care is a high-noise, high-stakes environment, and predictive tools must be rigorously validated before they can be relied upon in real-time decision-making [Halpern *et al.* 2025]. Accordingly, the strongest current claim is that ICU digital twins are an important frontier for research and translational development, not that they are already standard bedside systems [Halpern *et al.* 2025, Tudor *et al.* 2025].

Digital twin thinking is also expanding into surgery and musculoskeletal medicine. Recent reviews suggest that patient-specific digital models may improve preoperative planning, scenario testing, intraoperative guidance, postoperative monitoring, and training, especially in fields such as orthopedics where anatomy and biomechanics can be modeled in a relatively structured way [Dean *et al.* 2024, Asciak *et al.* 2025]. These applications are often discussed in terms of virtual rehearsal or digital twin-assisted surgery, where models can help clinicians anticipate implant placement, biomechanical consequences, or potential complications before an intervention is performed [Dean *et al.* 2024, Asciak *et al.* 2025]. Still, this remains an emerging domain, and the strongest evidence at present is better characterized as promising translational work rather than broad routine adoption across surgical practice [Dean *et al.* 2024].

Beyond human medicine, digital twins are beginning to appear in animal science and agricultural systems. Recent reviews of livestock-focused digital twin development describe applications in animal monitoring, environmental management, precision livestock farming, and integration with real-time sensor systems [Arulmozhi *et al.* 2024, Brown-Brandl *et al.* 2025]. In these settings, digital twins may be developed for individual high-value animals or, more commonly, for herd, barn, or environmental systems that integrate temperature, airflow, activity, productivity, and welfare-related measures [Arulmozhi *et al.* 2024, Brown-Brandl and Tao 2025]. As in healthcare, however, adoption is still early, and the literature describes the field as promising but immature, with practical use limited by data integration, infrastructure demands, and uncertainty about validation and return on investment [Arulmozhi *et al.* 2024, Brown-Brandl and Tao 2025].

Despite the enthusiasm surrounding digital twins, major limitations remain. Building a clinically useful or biologically meaningful twin requires reliable multimodal data, accurate mechanistic or statistical models, sustained synchronization between the virtual and physical systems, and validation that predictions are useful in practice [Drummond and Gonsard 2024, Khoshfekar Rudsari *et al.* 2025, Ringeval *et al.* 2025]. Ethical and legal questions also remain unresolved, including data privacy, governance, explainability, and accountability when model-guided recommendations influence care [Khoshfekar Rudsari *et al.* 2025, Ringeval *et al.* 2025]. Consequently, the most defensible conclusion is that digital twins are a highly promising framework for precision life sciences, but one whose impact will depend on validation quality, interoperability, ethical oversight, and the ability to translate sophisticated models into trustworthy real-world tools [Ringeval *et al.* 2025, Tudor *et al.* 2025].

Robotics and automation in life sciences

Robotics and automated systems are increasingly being integrated into laboratories, clinical care, and agricultural production, where they are changing how repetitive, precision-dependent, and labor-intensive tasks are performed. In the life sciences, their major advantages are improved throughput, greater procedural consistency, reduced exposure to hazardous or sterile-sensitive workflows, and better reproducibility of complex processes [Angelopoulos *et al.* 2024, Thurow *et al.* 2026]. Rather than serving as stand-alone tools, modern robotic platforms are typically embedded within broader digital ecosystems that include sensors, workflow software, data logging, and increasingly artificial intelligence-driven decision support [Angelopoulos *et al.* 2024, Tobias *et al.* 2025]. For that reason, robotics in life sciences is best understood as part of a larger shift toward intelligent, data-rich, and partially autonomous operational systems rather than simply mechanical task replacement [Canty *et al.* 2025, Thurow *et al.* 2026].

In biomedical and pharmaceutical laboratories, automation has become especially important because many workflows depend on handling large numbers of samples with high precision and minimal variability. Robotic liquid handlers, integrated screening platforms, automated imaging systems, and enclosed sterile robotic work cells are increasingly used to support tasks such as assay preparation, high-throughput screening, cell-based testing, and long-duration experimental workflows [Thurow *et al.* 2026]. Recent perspectives in “Science Robotics” argue that robotics can transform laboratories into “factories of discovery” by enabling experiments to be conducted faster, more safely, more accurately, and with greater reproducibility, while also helping address bottlenecks in scientific throughput [Angelopoulos *et al.* 2024]. More advanced systems now extend toward self-driving laboratories, in which automated hardware is linked to ML or optimization agents that iteratively propose, execute, and evaluate experiments. Although these systems are still emerging, recent work shows that autonomous platforms can already be used in domains such as protein

engineering and experimental optimization, demonstrating the feasibility of closed-loop robotic discovery systems in biology-related research [Rapp *et al.* 2024, Tobias and Wahab 2025].

Robotic systems are also valuable in research settings that require highly standardized execution, sterile manipulation, or reduced human exposure to hazardous materials. These benefits are particularly relevant in cell culture, compound handling, and workflows involving repetitive manual operations that are difficult to sustain with consistent human performance over long periods [Thurrow *et al.* 2026]. However, literature is careful not to frame automation as universally effortless or universally superior. Reviews of laboratory automation emphasize that interoperability, workflow integration, modularity, validation, and staff training remain major implementation barriers, especially in life science laboratories where workflows are less standardized than in industrial manufacturing [Tobias and Wahab 2025, Thurrow *et al.* 2026]. Thus, the strongest current conclusion is that robotics can substantially enhance laboratory capability, but successful deployment depends on system design, orchestration, and compatibility with real scientific workflows rather than hardware alone [Angelopoulos *et al.* 2024, Thurrow *et al.* 2026].

In clinical medicine, robotics has had its greatest visible impact in surgery. Robotic-assisted platforms provide enhanced dexterity, tremor filtration, articulated instrument control, and high-definition three-dimensional visualization, which can be advantageous in minimally invasive procedures performed in confined anatomical spaces [Rivero-Moreno *et al.* 2023, Picozzi *et al.* 2024]. At the same time, enthusiasm for robotic surgery has often outpaced uniform evidence of superiority across all procedures. A large cohort study showed that the use of robotic surgery for common general surgical procedures increased from 1.8% in 2012 to 15.1% in 2018, with especially large increases for some procedures such as inguinal hernia repair, even though evidence of improved outcomes remained procedure-specific rather than universal [Sheetz *et al.* 2020]. More recent analyses continue to suggest that robotic surgery is safe and increasingly adopted, but also emphasize cost, training demands, learning curve effects, and the importance of matching the technology to procedures where it provides measurable benefit rather than simply replacing established laparoscopic approaches [Picozzi *et al.* 2024, Wah 2025].

Beyond surgery, robotic technologies are increasingly used in rehabilitation and assistive care. These include exoskeletons, robotic gait trainers, upper limb rehabilitation devices, robotic prostheses, and socially assistive systems designed to support mobility, therapy intensity, or aspects of daily living [Banyai *et al.* 2024, Tseng *et al.* 2024]. The strongest evidence here supports robotics as a way to deliver repetitive, measurable, and high-intensity therapeutic practice while reducing some of the physical workload on therapists and providing objective feedback during rehabilitation [Banyai and Brişan 2024]. However, the literature is again cautious: clinical benefit depends on the patient population, rehabilitation goal, and implementation context, and high equipment costs, infrastructure requirements, and training demands remain

important barriers to broad routine adoption [Banyai and Brişan 2024, Amirbekova *et al.* 2025]. Therefore, it is safest to present rehabilitation robotics as an important and growing adjunct to care rather than a wholesale replacement for therapist-led rehabilitation [Banyai and Brişan 2024, Tseng *et al.* 2024].

In animal science and agriculture, robotics is increasingly associated with precision livestock farming and automated agricultural operations. One of the most established examples is the automatic milking system, which automates milking while simultaneously collecting detailed information about milk yield, milking behavior, and indicators relevant to cow health and management [Kappel *et al.* 2026]. The literature generally supports several recurring benefits of these systems, including reduced dependence on manual milking labor, improved management flexibility, and richer cow-level data streams that can support earlier detection of production or health changes [Lage *et al.* 2024]. At the same time, outcomes are not uniformly positive across all farms. Reviews and empirical studies note that automated milking can improve cow autonomy and reduce disturbance in some settings, but welfare and performance effects depend strongly on farm design, management quality, traffic systems, and broader herd conditions [Lavrijsen-Kromwijk *et al.* 2024, Kappel *et al.* 2026]. This means automated milking should be described as a mature but management-sensitive robotic technology rather than a guaranteed welfare or productivity upgrade in every context [Gislon *et al.* 2024, Lavrijsen-Kromwijk *et al.* 2024].

Agricultural robotics extends well beyond milking. Drones, autonomous ground systems, and AI-guided sensing platforms are increasingly used for crop monitoring, targeted input application, and field surveillance, supporting more precise and potentially more resource-efficient agricultural management [Guebsi *et al.* 2024, Padhiary *et al.* 2024]. In livestock systems more broadly, recent reviews describe growing convergence among robotics, sensors, AI, and precision livestock farming tools, although they also emphasize substantial barriers related to cost, system integration, farmer adoption, and validation in real production environments [Bernabucci *et al.* 2025, Distanto *et al.* 2025]. Thus, as in healthcare and laboratory science, the most defensible conclusion is that robotics and automation are becoming increasingly important across life sciences, but their value depends on how well they are integrated into operational, biological, and human decision-making systems [Angelopoulos *et al.* 2024, Bernabucci *et al.* 2025].

Beyond physical and computational systems, digital transformation in life sciences also extends to communication, engagement, and data exchange through online platforms.

Role of social media and digital communication in life sciences

Digital communication platforms now play a meaningful role in the life sciences, not only as channels for communication but also as sources of data and public engagement. Social media platforms such as X, Facebook, Reddit, LinkedIn,

and disease-specific online communities have changed how researchers, clinicians, patients, and the public exchange information. Recent reviews show that these platforms can support health promotion, peer support, professional networking, public communication, and data generation, but they also carry important risks related to misinformation, unequal reach, and variable content quality [Chen *et al.* 2021, Kbaier *et al.* 2024, Paul *et al.* 2025]. In life science contexts, social media is therefore best understood as a dual-use environment: it can accelerate knowledge exchange and observational insight, but it can also distort, polarize, or degrade public understanding when the quality of information is poor [Gaysynsky *et al.* 2024, Kbaier *et al.* 2024].

One important role of digital communication in the life sciences is knowledge dissemination and professional collaboration. Hashtag-based studies have shown that platforms such as X can help build interdisciplinary scientific communities, increase visibility of research themes, and support networking across countries and specialties. Examples include analyses of the #DHPSP (Digital Health and Patient Safety Platform) campaign in digital health and patient safety and the #INPST (International Natural Product Sciences Taskforce) network in natural product sciences, both of which showed how social media can be used to promote visibility and cross-disciplinary exchange [Kletecka-Pulker *et al.* 2021, Singla *et al.* 2023]. More recently, LinkedIn-based analysis of #HealthLiteracy suggested that professional social media platforms may support targeted dissemination of health literacy content and structured engagement in a more professionally oriented environment [Chandragiri *et al.* 2025]. Social media has also been used to amplify patient-centered communication themes, as shown by the international #HospitalsTalkToLovedOnes Twitter study during COVID-19, which highlighted how digital discourse can shape debates about family-centered care and patient inclusion [Hribersek *et al.* 2023].

Social media is also increasingly relevant to participant engagement and recruitment in research. Recent empirical studies show that social media can help researchers reach populations that may be difficult to recruit through traditional channels, although success depends heavily on trust, privacy expectations, digital literacy, and the social context of the target population [Willem *et al.* 2024, Pathak *et al.* 2025]. In a mixed-methods study of patients with hepatitis B, acceptance of social media recruitment was shaped by prior social media use related to the condition, interest in clinical studies, trust in information sources, and concerns around secrecy and stigma [Willem *et al.* 2024]. Likewise, exploratory work in mHealth (Mobile Health) research suggests that social media recruitment can broaden reach and diversify samples, although it may still be challenging and costly for some marginalized groups [Pathak *et al.* 2025]. These findings support a cautious conclusion: digital communication can be a useful recruitment tool, but it must be tailored carefully to ethical, cultural, and privacy concerns rather than treated as a universally effective strategy [Willem *et al.* 2024, Pathak *et al.* 2025].

Another major role of social media in life sciences is as a data source for digital epidemiology and infodemiology. Recent reviews indicate that social media, search engines, and other online platforms can provide early signals of infectious disease

activity and population-level concern, often complementing traditional surveillance systems rather than replacing them [Liscano *et al.* 2025]. A 2025 scoping review reported that digital surveillance models using social media and search data frequently showed meaningful lead times over traditional systems and often correlated strongly with official case data, particularly for influenza and COVID-19 [Giancotti *et al.* 2024, Liscano *et al.* 2025]. At the same time, public-health social listening studies make clear that these systems require careful validation because data quality, platform access, representativeness, and algorithmic noise can substantially affect performance [Boatman *et al.* 2024, Giancotti *et al.* 2024]. The most defensible claim, then, is that social media analytics can strengthen outbreak intelligence and behavioral monitoring when used as a complementary surveillance layer, not as a stand-alone epidemiological authority [Boatman *et al.* 2024, Liscano *et al.* 2025].

These platforms can also be used more directly as research environments for opinion polling, crowdsourcing, and behavioral observation. X-based studies have been used to collect views on public health measures, vaccine mandates, and self-reported practices in ways that are fast, low-cost, and responsive to changing public discussions [Mondal *et al.* 2022, Ritschl *et al.* 2022, Singla *et al.* 2025]. For example, Twitter-based crowdsourcing was used to gather public suggestions about measures that could help end the COVID-19 pandemic faster, while X poll analysis was used to examine public opinion on mandatory COVID-19 vaccination [Mondal *et al.* 2022, Ritschl *et al.* 2022]. More recently, an X-based survey on nutritional supplement use for respiratory tract infections illustrated how social platforms can be used to collect real-time self-reported behavior data at scale [Singla *et al.* 2025]. These studies are useful examples of methodological innovation, but they should not be overinterpreted: platform-based surveys are often subject to self-selection bias, demographic skew, and limits in generalizability [Ritschl *et al.* 2022, Liscano *et al.* 2025].

The most persistent challenge in this area is misinformation. Recent reviews emphasize that health misinformation on social media remains a major public-health concern, particularly because the same systems that enable rapid dissemination of evidence can also amplify rumors, conspiracy claims, and emotionally compelling falsehoods [Yeung *et al.* 2022, Kbaier *et al.* 2024, Denniss *et al.* 2025]. Empirical work also shows that many users perceive high levels of health misinformation online and that difficulty distinguishing accurate from inaccurate content remains common [Gaysynsky *et al.* 2024]. During and after the COVID-19 pandemic, this problem became especially visible, and the literature now treats misinformation management as a central issue in digital health communication rather than as a side effect of platform use [Boatman *et al.* 2024, Kbaier *et al.* 2024]. Accordingly, the most balanced conclusion is that social media has become structurally important to life-science communication and surveillance, but its value depends heavily on digital literacy, content quality, platform governance, and the ability of public-health and scientific communities to respond quickly with credible information [Gaysynsky *et al.* 2024, Kbaier *et al.* 2024, Paul and Headley-Johnson 2025].

At the same time, the persistence of misinformation underscores the continuing importance of direct clinician-patient communication in the digital era. Evidence suggests that the impact of online health information on the patient-physician relationship depends strongly on whether patients are able to discuss what they have found during consultations, because non-discussion limits opportunities for patient-centered care and for correction of misunderstandings [Tan *et al.* 2017, Linn *et al.* 2024]. Recent work further indicates that participative communication strategies, in which physicians acknowledge patients' internet searches and help interpret their relevance, are more constructive than defensive approaches that simply discourage online information seeking [Lu *et al.* 2024]. Consistent with this, patient-centered communication is associated with higher trust in clinicians as information sources, and interpreting internet information for patients remains an important clinician function [Asan *et al.* 2021]. Direct face-to-face or otherwise person-centered health communication should therefore be viewed as a necessary complement to digital information environments, because patients often need support from physicians and other health professionals to judge which online information is relevant, reliable, and applicable to their individual situation [Linn *et al.* 2024, Lu and Schulz 2024].

On the positive side, digital communication platforms also support community formation and peer-to-peer support, especially for geographically dispersed or medically underserved groups. A 2025 scoping review of parents and caregivers of children with rare genetic diseases found that social media groups were widely used for medical information, practical care tips, and emotional support, and that they helped reduce isolation across time and geographic barriers [Davis *et al.* 2025]. This kind of digital community-building is increasingly relevant in life sciences because it can influence research agendas, patient engagement, and communication between families and professionals [Hribersek *et al.* 2023, Davis *et al.* 2025]. Thus, social media in life sciences should not be framed only as a misinformation risk or only as an innovation tool; it functions as a complex communication infrastructure which has multifaceted impact on dissemination, surveillance, recruitment, public behavior, and patient support all at once [Davis *et al.* 2025, Paul and Headley-Johnson 2025].

Future perspectives, challenges, and opportunities

The integration of digital technologies into life sciences is still accelerating, and the next phase will likely be defined less by isolated tools than by increasingly connected digital ecosystems. Across medicine, agriculture, and biotechnology, future progress will depend on the convergence of artificial intelligence, sensor networks, automation, interoperable data platforms, and predictive modeling rather than on any single technology in isolation [Papakonstantinou *et al.* 2024, Adegoke *et al.* 2025, Yeung *et al.* 2025]. In practical terms, this means that the most influential systems of the coming years are likely to be those that combine continuous data generation, automated action, and scalable analytics into unified workflows. Examples include

digitally integrated hospitals, self-optimizing laboratories, and precision livestock systems that combine IoT devices, AI-based decision support, robotic execution, and auditable data infrastructures [Papakonstantinou *et al.* 2024, Guo *et al.* 2025]. This convergence also means that future innovation will increasingly require interdisciplinary teams in which life scientists, clinicians, engineers, computer scientists, and data specialists can work across traditional disciplinary boundaries [Yeung *et al.* 2023, Zhang 2026].

The second major subject is governance. As life sciences become more digital and data-intensive, the long-term value of these systems will depend on interoperability, data stewardship, privacy protection, and trustworthy implementation. Recent reviews emphasize that fragmented data environments remain a major barrier, especially when different institutions, software platforms, or device ecosystems cannot exchange data efficiently or reliably [Adegoke *et al.* 2025, Roy *et al.* 2025]. In healthcare, the need to combine data utility with privacy has made approaches such as federated learning, privacy-preserving analytics, and common data models increasingly important, but these methods still require robust governance to manage risks related to bias, security, accountability, and uneven institutional capacity [Abbas *et al.* 2024, Eden *et al.* 2025]. Similar issues extend beyond medicine into agricultural and research settings, where questions of data ownership, data access, and platform dependence remain unresolved. As a result, future progress will rely not only on better algorithms, but also on better rules, standards, and governance models that allow data to be used responsibly across organizational boundaries [Adegoke *et al.* 2025, Eden *et al.* 2025].

Regulation and reimbursement will also shape the pace of adoption. Across digital health and AI-enabled systems, technical feasibility alone is not enough for durable implementation. Recent policy and implementation analyses note that even when tools are clinically promising, adoption may stall if regulatory pathways are unclear, post-deployment monitoring is weak, or payment structures fail to support integration into routine workflows [Razavian *et al.* 2025, Wells *et al.* 2025]. This is especially relevant for AI in clinical care, where health systems must balance innovation with safety, transparency, and accountability over time rather than only at initial deployment [Wells *et al.* 2025]. More broadly, a recent review of global AI medical-device regulation noted continuing gaps in harmonization, oversight, and practical implementation across regions [Zhang *et al.* 2025]. These observations suggest that future opportunities will depend not only on inventing new tools, but also on building regulatory and policy environments that can evaluate, reimburse, and monitor them in a flexible but credible manner [Wells *et al.* 2025, Zhang 2026].

Equity and infrastructure are another defining challenge. Digital technologies can improve access, continuity, and analytical capacity, but they can also widen disparities if connectivity, hardware, training, and implementation support are unevenly distributed. Recent reviews on digital health inequality warn that digital tools often benefit populations and institutions that are already better resourced, while low-resource settings face recurring barriers related to broadband access, infrastructure,

staffing, maintenance, and contextual fit [Badr *et al.* 2024, Roy *et al.* 2025]. At the same time, the literature also highlights important opportunities: open-source systems, cloud-enabled workflows, remote platforms, and lower-cost digital infrastructures can help extend capabilities to settings that historically lacked advanced local resources [Roy *et al.* 2025]. In this sense, digital equity should be treated as a core design and policy issue rather than an afterthought. The future benefits of digital life sciences will be larger and more sustainable if systems are built for inclusion, adaptability, and usability across diverse real-world settings [Badr *et al.* 2024, Bitomsky *et al.* 2024].

Another major future issue is the relationship between scale and interpretation. Data volumes will continue to expand through multi-omics, real-world monitoring, imaging, wearables, and digital communication platforms, but more data do not automatically produce better understanding. Reviews in bioinformatics and AI-enabled health research consistently emphasize that the key bottlenecks are increasingly interpretability, validation, harmonization, and actionable translation rather than raw data generation alone [Alhumaidi *et al.* 2025, Zhang 2026]. This is why human expertise will remain central. Rather than replacing scientists, clinicians, veterinarians, or farmers, the strongest digital systems are likely to be those that augment human judgment with better pattern recognition, faster synthesis, and more timely decision support. Recent evidence in imaging supports this general principle: human-AI collaboration can improve performance and efficiency, when workflows are carefully designed and the roles of human oversight and algorithmic support are clearly defined [Chen *et al.* 2024, Kocak *et al.* 2026]. The most promising future is therefore not one of full automation everywhere, but one of thoughtfully designed human-machine collaboration [Chen and Wang 2021, Wells *et al.* 2025, Kocak and Cuocolo 2026].

Looking further ahead, digital life sciences are likely to become more predictive, more preventive, and more personalized. The expansion of real-world evidence, wearable monitoring, interoperable data systems, and computational modeling may allow health and biological systems to be studied in more dynamic, longitudinal, and context-sensitive ways than traditional experimental designs alone permit [Austin *et al.* 2024, Costa *et al.* 2025]. In medicine, this could support earlier detection, more individualized treatment strategies, and stronger integration of trial evidence with real-world data. In agriculture, it could support more resilient and climate-responsive production systems through continuous monitoring and adaptive management [Guo *et al.* 2025, Nsabiyeze *et al.* 2025]. In biologically rich domains such as natural-products research, future digital tools may also accelerate discovery, screening, and translational interpretation by linking traditional biological knowledge with computational and data-intensive methods [Matin *et al.* 2025].

Overall, the future of digital life sciences is highly promising, but its success will depend on more than technical sophistication. The field will advance most effectively where innovation is matched by interoperability, governance, equitable access, rigorous validation, and workforce development. If these constraints are addressed

thoughtfully, digital technologies will not merely improve existing workflows; they will reshape how life-science knowledge is generated, shared, and applied across human health, animal systems, and biotechnology [Yeung *et al.* 2023, Badr *et al.* 2024, Wells *et al.* 2025].

Conclusions

This review was motivated by the absence of an integrative synthesis examining the convergence of multiple digital technologies such as AI, IoT, blockchain, bioinformatics, digital twins, robotics, and digital communication across animal science, medical science, and biotechnology simultaneously. By providing this cross-domain perspective, it offers a unifying framework to a literature that has largely addressed these technologies in isolation or within single application domains. Digital technologies are no longer peripheral tools in life sciences; they are redefining how biological systems are studied, monitored, and managed. Across medicine, animal science, and biotechnology, the integration of computational methods, connected devices, and automated systems is shifting the field toward more data-driven, predictive, and adaptive approaches. Rather than functioning independently, these technologies are increasingly converging into integrated digital ecosystems that link measurement, analysis, and action in ways that were previously not possible.

A key insight from this review is that the transformative value of digital technologies lies in their ability to connect complexity with decision-making. AI and big data analytics are enhancing the interpretation of biological information, IoT systems are enabling continuous real-world monitoring, and robotics and automation are improving precision and reproducibility in both laboratory and production environments. Emerging frameworks such as digital twins further extend this shift by allowing biological processes to be modeled and explored in virtual environments. Together, these developments are moving the life sciences from largely reactive models toward more predictive and preventative paradigms.

Importantly, this transformation is not confined to human health. Animal science is becoming an essential component of the digital life science landscape, with precision livestock systems, automated welfare monitoring, and data-driven disease management demonstrating how digital tools can enhance both productivity and ethical standards. The convergence of digital approaches across human and animal domains also highlights the growing importance of integrated, cross-species perspectives in addressing complex biological and environmental challenges.

Despite this progress, the long-term impact of digital technologies will depend on how effectively key challenges are addressed. Interoperability, data governance, privacy, validation, and equitable access remain critical constraints that will shape adoption and trust. Equally important is the need to develop a workforce capable of operating at the interface of biology and data science, ensuring that technological advances are translated into meaningful and responsible applications.

Looking ahead, the continued integration of digital technologies is likely to reshape not only research workflows but also the broader structure of life sciences as a discipline. As data streams become richer and more interconnected, and as computational tools become more capable, the boundaries between experimentation, simulation, and real-world application will continue to blur. This shift has the potential to accelerate discovery, improve health and welfare outcomes, and support more sustainable biological systems.

Ultimately, the future of life sciences will be defined not simply by the adoption of digital technologies, but by how effectively they are integrated, governed, and aligned with human and societal needs. If these conditions are met, digital transformation will serve not just as a technological advancement, but as a fundamental evolution in how life is understood, managed, and improved.

Author contribution

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