Integrating artificial intelligence and machine learning into modern health information, One Health, and bioengineering ecosystems: Advances and future directions

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ABSTRACT

Artificial intelligence (AI) and machine learning (ML) are reshaping health information and bioengineering ecosystems across human, veterinary, and environmental domains. Beyond streamlining diagnostics and treatment, these technologies are driving advances in precision medicine, regenerative medicine, drug delivery, and digital health, transforming them into more adaptive and predictive systems. This article provides a comprehensive perspective and prospective review of recent breakthroughs in AI and ML. It includes AI-driven diagnostics, telemedicine platforms, dentistry, One Health surveillance tools, and innovations in bioengineering. A thematic synthesis of innovations highlights the growing importance of interoperability, clinical adaptability, and equitable access. Central to these developments is the emerging concept of meta-AI frameworks, supported by model context protocols (MCP), which can orchestrate multiple AI tools into responsive, context-aware systems. Such integration promises not only efficiency but resilience in managing complex health challenges. This article outlines the gaps and challenges posed by advances in AI systems, particularly in resource-limited settings in most developing countries and proposes solutions. From a prospective standpoint, we argue that the next decade will see health information and bioengineering ecosystems evolve into proactive decision-support environments, capable of anticipating risks and guiding personalized interventions. This convergence of AI/ML with bioengineering and One Health strategies positions intelligent informatics as both a present innovation and a cornerstone for future global health security.

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INTRODUCTION

The current era of medicine, veterinary medicine, and dental care is based on well-established approaches in pharmacology, surgery, and public health, which have immensely helped treat acute conditions, infectious diseases, and chronic disorders. Currently,

KEYWORDS

Artificial intelligence, Machine learning, Health information ecosystems, Bioengineering, Precision medicine, Digital health, One Health

healthcare strategies encompass different clinical approaches and extensive in-person medical and dental treatments, including veterinary medical interventions (Janiaud et al., 2019; Endoh et al., 2024). Various anti-inflammatory agents, antibiotics, analgesics, anti-cancer, and antiviral medicines are the front-runners of conventional pharmaceutical interventions. Homeopathy, Ayurveda, herbalism, and vitamin supplementation are commonly identified as the backbone of alternative and complementary therapies that occupy alternative therapeutic pathways.

However, some limitations and deficiencies in the conventional medical approaches, such as the emergence of new infectious diseases, increasing age-related afflictions (Franceschi et al., 2018), increasing antibiotic resistance (Ferri et al., 2017), poor chronic disease management, and increasing therapeutic failure in cancer treatment (Igarashi & Sasada, 2020), need to be improved. Hence, there is an urgent need to develop new therapeutics and strategies to address current healthcare problems and improve healthcare systems (Table 1).

Table 1: Challenges in Conventional Healthcare and Emerging AI/ML–Bioengineering Solutions

Conventional Healthcare Challenges	Emerging AI/ML and Bioengineering Solutions
Emergence of new infectious diseases	AI-driven surveillance & predictive epidemiology
Age-related disorders & chronic disease burden	Regenerative medicine, stem cell therapies, bioengineering
Antibiotic resistance	AI-guided antimicrobial stewardship, rapid diagnostics
Therapeutic failures in cancer	Precision medicine & targeted therapies supported by ML
Fragmented human–animal–environment health approaches	One Health with AI-enabled integration

This document will comprehensively tackle AI- and ML-driven diagnostics, telemedicine and teledentistry, One Health, bioengineering innovations, nanotechnology-enabled drug delivery, precision and personalized medicine, and the use of meta-AI and the model context protocol (MCP).

Artificial Intelligence and Machine Learning

AI refers to the broad field of computational systems designed to emulate, augment, or automate human cognitive functions such as reasoning, perception, problem-solving, and adaptive decision-making (Russell & Norvig, 2021). Within this umbrella, Machine Learning (ML) represents a specific subset focused on data-driven model training, statistical pattern recognition, and predictive analytics derived from large or complex datasets (Jordan & Mitchell, 2015). While AI includes robotics, expert systems, natural language processing, and automated decision-support tools, ML provides the mathematical and statistical frameworks—such as supervised, unsupervised, reinforcement, and deep learning—that enable these systems to learn from data and progressively improve their performance (Samuel, 1959; Goodfellow et al., 2016). Clarifying this distinction establishes a conceptual foundation for understanding how diagnostic automation, predictive modelling, bioengineering optimization, and One Health surveillance are applied throughout this review.

Machine Learning within the Data Science Analytical Framework

ML operates at the core of data-driven discovery, and its function becomes clearer when viewed through the five analytical objectives (Table 2) of the Data Science paradigm: descriptive, diagnostic, explanatory, predictive, and prescriptive analytics (Provost & Fawcett, 2013). Descriptive analytics uses clustering and feature extraction to summarize complex health and environmental datasets, such as patient phenotypes or pathogen distributions (Hanson et al., 2024). Diagnostic analytics applies classification and anomaly-detection approaches widely used in AI-assisted imaging, digital pathology, and PCR performance assessment (Schwendicke et al., 2020; Sanekata et al., 2024). Explanatory analytics employs model interpretability tools such as SHAP (SHapley Additive exPlanations) values, decision trees, and feature-importance analyses to identify contributing risk factors or sources of molecular diagnostic variability (Ramaswami et al., 2018; Kayama et al., 2021). Predictive analytics uses time-series forecasting and supervised learning to anticipate disease outcomes, drug responses, and PCR/LAMP amplification success (Jiménez-Luna et al., 2021; Camer et al., 2019; Endoh et al., 2024). Finally, prescriptive analytics leverages optimization and reinforcement learning systems to recommend pharmacogenomic dosing strategies and to design efficient primer or diagnostic workflows (Abdelgalil et al., 2020; Kayama et al., 2020). By situating ML roles within these five objectives, the manuscript presents a coherent methodological narrative that links Health Information Systems, One Health surveillance, and Bioengineering innovations.

Table 2: Data Science Goals, ML Roles, and Examples Across Health Information, One Health, and Bioengineering Ecosystems

Data Science Goal	ML Role	Health Information Examples	One Health Examples	Bioengineering Examples
Descriptive	Clustering, feature extraction, visualization	Clustering patient groups using wearable sensor data (Hanson et al., 2024)	Summarizing pathogen distribution using LAMP/PCR datasets (Sanekata et al., 2024; Kayama et al., 2021)	Extracting structural patterns from CT/MRI/CBCT images (Hendee et al., 2008)
Diagnostic	Classification, anomaly detection	AI-assisted imaging and pathology detection (Schwendicke et al., 2020; Jiang et al., 2017)	PCR success/failure ML analysis; synthetic gene template classification (Kayama et al., 2021; Camer et al., 2019)	AI segmentation of tumor vs. normal tissue (Hendee et al., 2008)
Explanatory	SHAP, decision trees, feature importance	Identifying risk contributors in precision medicine (Khatri & Petrelli, 2020; Ramaswami et al., 2018)	Identifying influential parameters affecting LAMP/PCR amplification (Kayama et al., 2021)	Explaining nanoparticle interaction mechanisms (Abtahi et al., 2024; Chehelgerdi et al., 2023)
Predictive	Predictive modeling, time-series forecasting	Disease/drug response prediction (Jiménez-	PCR amplification success prediction;	Predicting drug release kinetics and bioprinting

		Luna et al., 2021; Saeed et al., 2023; Liu & Wang, 2024)	AI+synthetic DNA workflows (Kayama et al., 2021; Camer et al., 2019; Sanekata et al., 2024)	outcomes (Abtahi et al., 2024; Hendee et al., 2008)
Prescriptive	Optimization, recommendation, reinforcement learning	Pharmacogenomic dosing optimization (Abdelgalil et al., 2020; Braig, 2022)	Primer optimization and diagnostic workflow design (Kayama et al., 2021; Kayama et al., 2020; Camer et al., 2019)	Optimization of nanocarrier design and bioprinting parameters (Chehelgerdi et al., 2023; Abtahi et al., 2024; Thalakiriyawa & Dissanayaka, 2024)

One Health Background

The One Health framework provides an integrated view of health by recognizing that human, animal, environmental, and ecological systems function as deeply interconnected components of a single biological and societal network. Disease emergence, antimicrobial resistance, food safety, and environmental degradation often arise from interactions at this interface, making coordinated and simultaneous management across these sectors essential. International bodies such as the WHO, OIE/WOAH, FAO, and UNEP emphasize One Health as a unifying strategy for surveillance, diagnostics, and policy design, particularly for zoonotic and environmentally linked infections (Camer et al., 2003; Camer et al., 2008; Endoh et al, 2024). Loop-Mediated Isothermal Amplification (LAMP) is a rapid and highly sensitive nucleic acid amplification technique now widely used for the detection of human, veterinary, and environmental pathogens, especially when enhanced through AI-guided primer design and machine-learning–supported optimization. Recent advances in molecular diagnostics, including AI-supported LAMP assays and algorithm-guided synthetic nucleic acid design, directly contribute to One Health surveillance by enabling rapid detection of pathogens circulating across human, veterinary, and environmental reservoirs (Kayama et al., 2021; Endoh et al., 2024; Sanekata et al., 2024). By grounding our review in this framework, the manuscript situates AI, ML, and bioengineering innovations within a holistic system required for contemporary global health security.

Recognizing the interconnectedness among humans, animals, and the environment has underscored the need for collaboration among experts to support the One-Health initiative (Camer et al., 2019; Camer et al., 2020; Endoh et al., 2024; Sanekata et al., 2024). Newer AI- and machine-learning-supported technologies have been emerging to benefit mankind. This article offers both a perspective on current AI/ML-driven advances and a prospective outlook on their future directions in health information, bioengineering, and One Health.

Taken together, we argue that artificial intelligence and machine learning, when embedded in modern therapeutics, bioengineering, and digital health, can transform fragmented medical, dental, and veterinary practices into a more integrated learning health information ecosystem that supports One Health and global health security. In this review, we first outline current therapeutic and bioengineering advances, then describe how AI and ML are being deployed within these domains, and finally synthesize their contribution to modernized health information and One Health systems (Figure 1).

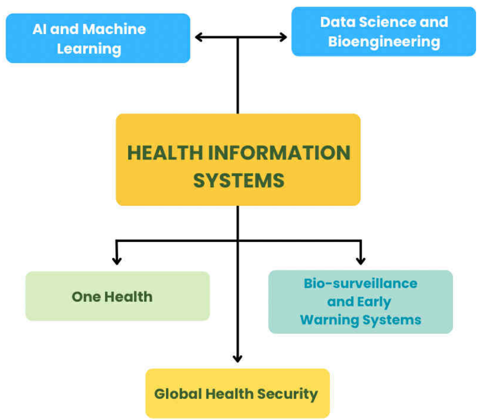

Figure 1: Integrative Framework for Health Information Systems.

This figure illustrates how Artificial Intelligence, Machine Learning, Data Science, and Bioengineering feed into modern Health Information Systems, which in turn support One Health and Global Health Security.

Temporal Evolution of AI and ML in Health Informatics and One Health Ecosystems

AI and ML have undergone rapid evolution in their applications to health over the past decade. Early AI use in healthcare (2010–2015) focused on structured data mining, rule-based systems, and automated imaging pipelines, reflecting the foundational developments in statistical learning and early deep learning (LeCun et al., 2015). Between 2016 and 2021, the widespread adoption of convolutional neural networks (CNNs), recurrent neural networks (RNNs), and transformer architectures (Vaswani et al., 2017; Kayama et al., 2021) enabled major advances in radiology, digital pathology, genomic analysis, and clinical prediction models (Esteva et al., 2019). Current applications (2022–present) integrate multimodal data—not only clinical and imaging data but also veterinary, environmental, and genomic datasets—driven by One Health approaches and enhanced molecular diagnostics such as AI-supported PCR and LAMP primer design (Endoh et al., 2024; Sanekata et al., 2024). Looking forward (next 3–5 years), AI is expected to progress toward meta-AI or orchestration frameworks that coordinate multiple specialized models to provide adaptive, context-aware decision support across human, animal, and environmental health domains (Russell & Norvig, 2021). This temporal perspective situates the technologies reviewed in this paper within both their historical trajectory and their anticipated future development (Figure 2).

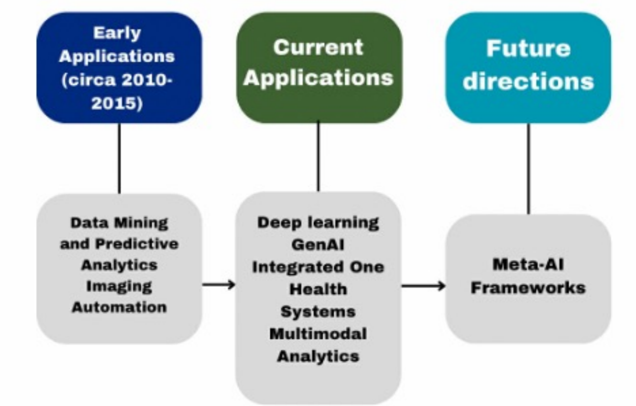

Figure 2: Temporal Evolution of AI and ML in Health Informatics and One Health Ecosystems.

Recent scholarship has already mapped important parts of this landscape. Broad clinical reviews have outlined how AI and ML can transform diagnostics, workflow, and clinical decision-making in medicine, but they largely focus on human healthcare and specific specialties rather than cross-sector health information ecosystems (Jiang et al., 2017; Topol, 2019; Bajwa et al., 2021). In parallel, several emerging frameworks examine how digital technologies and AI can support One Health data integration, antimicrobial resistance monitoring, and infectious-disease surveillance across human, animal, and environmental sectors (Scott et al., 2023; Redman-White et al., 2023; Kasse et al., 2025; Idahor & Esomu, 2025). However, these reviews typically treat clinical AI, One Health, and digital surveillance as separate threads.

The present article builds on this literature by integrating these strands into a unified discussion that links AI/ML, data science, health information systems, One Health, and bio-surveillance. This synthesis differentiates the current review by offering a broader, interconnected framework rather than discipline-specific perspectives, and by introducing emerging concepts such as meta-AI and model-context–based architectures as future directions for global health security (Table 3).

Table 3: AI and ML in Healthcare, One Health, and Bioengineering Ecosystems

Domain	Objectives	Representative Methods / Algorithms	Applications in Health Information Systems	Applications in One Health Surveillance	Applications in Bioengineering / Biomedical Systems
Artificial Intelligence (AI)	1. Automation of routine tasks 2. Real-time decision support 3. Integration of multimodal data (clinical, genomic, imaging, environmental) 4. Augmentation of human reasoning	1. Expert systems 2. Robotics and automation 3. Natural Language Processing (NLP) 4. Computer vision 5. Knowledge-based systems	1. Automated triage 2. Workflow optimization 3. Clinical decision-support systems 4. Medical imaging automation	1. Environmental risk assessment 2. Outbreak detection systems 3. AI-enabled ecological modeling	1. Surgical robotics 2. Smart prosthetics 3. Automated biomaterial analysis 4. Image-guided interventions
Machine Learning (ML) (subset of AI)	1. Classification 2. Clustering 3. Regression 4. Prediction and forecasting 5. Optimization	1. Supervised learning (SVM, Random Forest, Logistic Regression) 2. Unsupervised learning (K-means, PCA) 3. Reinforcement learning 4. Deep learning (CNNs, RNNs, LSTMs, Transformers)	1. Disease prediction models 2. Electronic health record (EHR) analytics 3. Drug response forecasting 4. Patient risk stratification	1. AI-optimized PCR/LAMP primer design 2. Zoonotic outbreak prediction 3. Pathogen detection using ML-enhanced diagnostics 4. Animal movement and ecosystem modeling	1. Genomic sequence analysis 2. Biomaterial optimization 3. Tissue engineering simulations 4. ML-guided nanomaterial and drug design
Deep Learning (DL) (subset of ML)	1. Automated feature extraction 2. High-dimensional pattern recognition 3. Multimodal data fusion	1. Convolutional Neural Networks (CNNs) 2. Recurrent Neural Networks (RNNs) 3. Transformers 4. Autoencoders	1. Digital pathology 2. Radiology and CBCT interpretation 3. Dermatologic imaging 4. Genomic biomarker detection	1. Wildlife image detection 2. Syndromic surveillance from social media 3. Satellite-based environmental anomaly detection	1. Bioprinting parameter optimization 2. Protein structure prediction 3. Smart implant monitoring
Meta-AI / Model Context Protocol (MCP)	1. Coordinate multiple AI models 2. Context-aware model selection 3. Robust decision-making across dynamic environments	1. Agent-based orchestration systems 2. Large Model Context Graphs 3. Interoperable AI pipelines	1. Integrating diagnostic AI with EHR, imaging AI, and genomic 2. Personalized clinical pathways	1. Cross-sector data integration (human–animal–environment) 2. Real-time One Health surveillance platforms	1. Linking engineering models, imaging 2. AI, and biomaterial simulations 3. Robotics and automated fabrication

These AI-driven applications in disease detection, predictive analytics, outbreak monitoring, and One Health surveillance collectively fall under modern bio-surveillance and early warning systems. This overall relationship among AI, machine learning, data science, bioengineering, and their contributions to One Health and global health security is summarized in a conceptual schematic framework (Figure 3).

Figure 3: Unified AI-Driven Healthcare Ecosystem Linking Diagnostics, Telemedicine, Precision Medicine, Nanotechnology, One Health, and Meta-AI

Overview of Modern Medicine and Dental Care

Innovations are making great strides in precision, personalized, and targeted medicine, gene-editing technologies, biologics, and monoclonal antibodies. Scientists have recently made significant advances in drug formulation and delivery systems by adopting nanotechnologies, nanoparticles, nano-machines, and nano-bots. Advancements in regenerative medicine, bioengineering, and integration of artificial intelligence, digital health, and telemedicine are changing the face of medical treatments (Sisodiya, 2021; Naaz & Asgharm, 2022).

Modern technologies are also significantly improving dental care by enhancing periodontitis management, oropharyngeal cancer control, and tooth regeneration through stem cell therapies and tissue engineering (Thalakiriyawa & Dissanayaka, 2024). Moreover, the integration of AI into diagnostics has enabled earlier detection of dental diseases, such as oral cancer, enabling quick intervention (Schwendicke et al., 2020). Advances in technology likewise extend to modern veterinary medicine. With this, the collaborative strategies of all healthcare and life science professionals, along with emergent technologies, are now merging to transform how diseases are managed, so that preventive and therapeutic care go hand in hand.

In the rest of the paper, the focus is not only on describing these technologies but also on explaining their implications for clinical decision making, patient outcomes, and population-level health indicators across medicine, dentistry, veterinary medicine, and One Health.

1. Precision Medicine, **Personalized Medicine**, and **Targeted Therapies**

The terms precision medicine, personalized medicine, and targeted therapies are used in different ways in healthcare, yet they are closely related. They customarily overlap, though each would aim to tailor medical treatment to the unique traits of individual patients. Below is the description of categories and what they cover:

a. Precision Medicine. Precision medicine is the practice of medicine that considers an individual's genes, environment, and lifestyle to guide decisions for disease prevention, diagnosis, and treatment (Ramaswami et al., 2018; Khatri & Petrelli, 2020). Fundamental elements of precision medicine include

Genomics. This deals with the complete analysis of the genome, the entire collection of genes, and how the genes respond to their environment and different pathogens. Genomics also supports understanding how different factors contribute to genetic variation, such as single-nucleotide polymorphisms (SNPs), gene mutations, and genetic disorders. For example, anemia is caused by a mutation in the HBB (beta-globin) gene (Jaing, 2021), and cystic fibrosis is caused by a mutation in the CFTR (cystic fibrosis transmembrane conductance regulator) gene (De Boeck, 2020).

Biomarkers. Biomarkers are indicators or predictive factors of various medical conditions. Biomarkers can be classified as genetic markers, proteins, or specific molecules in body tissues/fluids, and their increased value can support physicians in detecting and monitoring various diseases. For example, HER2 is a biomarker for breast cancer (Moasser, 2007), and PSA (Prostate-Specific Antigen) is a biomarker for prostate cancer (Duffy, 2020).

Pharmacogenomics. This entails the in-depth investigation of how a person will respond to a prescribed medicine based on their genetic makeup. Pharmacogenomics enables physicians to prescribe specific medicines that are beneficial for everyone based on their genetic variations. This customized dosage, based on genetic makeup, increases efficacy and minimize potential side effects of certain drugs. For example, variations in the CYP2C9 and VKORC1 genes significantly influence warfarin metabolism in any patient. It is observed that warfarin is slowly metabolized in patients with CYP2C9 variants, suggesting that such patients require lower warfarin doses to prevent bleeding (Takeuchi et al., 2020).

Environmental and Lifestyle Data. In precision medicine, data associated with patients' non-genetic factors, such as environmental exposures (e.g., diet, pollution) and personal behaviors (e.g., exercise, smoking), is considered vital to enhance the efficiency and productivity of treatment and preventive plans. For example, it is extremely important for pulmonologists to consider environmental factors in their asthmatic patients, as pollution, second-hand smoke, dust mites, and cold air are linked to increased asthma severity (Strachan, 2000).

Data Integration and AI. AI is playing a fundamental role in identifying disease patterns across broader patient datasets, which can be effectively used to predict disease risks and tailor treatment strategies. For example, an AI model can forecast the risk of different cardiac diseases in individuals with a sedentary lifestyle, high cholesterol, high blood pressure, and a family history of cardiovascular diseases. Additionally, AI can propose lifestyle modifications, dietary changes, medications, and therapeutic approaches to reduce the risk of developing various heart diseases (Guo et al., 2022).

b. Personalized Medicine. As the name suggests, personalized medicine is the tailored treatment of an individual patient by customizing medical decisions, treatments, practices, or products based on genetic, environmental, and lifestyle factors (Goetz & Schork, 2018; Braig, 2022). The following are the key components of personalized medicine:

Custom Treatment Plans. The treatment plans are customized to the patients' genetic profiles, which may determine how they respond to certain interventions and medications. For example, trastuzumab (Herceptin) is an effective treatment for HER2-positive breast cancer (Jaques & Matsakas, 2020).

Diagnostic Tests. Several molecular and genetic tests identify the treatments or medicines that will be effective for a patient. If a patient with melanoma is found to be positive for a BRAF V600E mutation, the patient may be treated with vemurafenib or dabrafenib, which target that mutation perfectly and inhibit tumor growth (Bouffet et al., 2023).

Prevention. Certain diseases (e.g., cardiovascular disease, breast cancer) in a population can be prevented by genetic screening, and based on the outcome of the test, individuals can be offered specific preventive therapy. For example, genetic testing at an early age can help determine a person's risk of developing familial hypercholesterolemia (FH). Such patients are advised to eat less oily foods, engage in regular exercise, and are prescribed statins or PCSK9 inhibitors to lower their cholesterol (Sawhney & Madan, 2024).

Continuous Monitoring. Recent advancements in digital health technologies and wearable devices are helping chronic patients monitor their health conditions and adjust their medications. Diabetic patients are benefiting from available technologies and devices (e.g., Dexcom G6 or FreeStyle Libre) that enable continuous monitoring of blood glucose levels and automatically adjust insulin dosing (Hanson et al., 2024).

c. Targeted Therapies

These medicinal therapies are designed to target the specific causes of cancer and other diseases, as well as certain general cellular changes. These therapies only destroy the source of disease/s and are always more targeted than conventional treatments like chemotherapy, which not only impact the target cancer cell but also destroy healthy cells (Saeed et al., 2023; Liu & Wang, 2024).

Targeting a Specific Gene or Protein. Targeted therapy typically targets proteins, receptors, enzymes, or genes that promote the growth and spread of cancer or other diseases in a highly specific manner. In HER2-positive breast cancer patients, trastuzumab targets HER2 receptors on cancer cells, which are involved in cancer cell proliferation and growth. Due to its enhanced targeting of cancer cells compared to conventional methods, it is very helpful in therapy for HER2-positive breast cancer (von Arx et al., 2023).

Monoclonal Antibodies. These are molecules manufactured in the laboratory that aim to mimic the immune system to fight disease. Commonly used in cancer therapy, they are specialized selections based on antigens found on cancer cells. Rituximab, for example, is a monoclonal antibody commonly used in the treatment of non-Hodgkin lymphoma and chronic lymphocytic leukemia (CLL) because it targets the B cells responsible for these diseases (Hagemeister, 2010).

Tyrosine Kinase Inhibitors (TKIs). Tyrosine kinase enzymes are important cellular components that promote the growth and multiplication of cancer cells. Thus, TKIs, which can block tyrosine kinases, are among the most significant therapeutic agents for the treatment of various cancers, such as leukemia, lung, and gastrointestinal cancers. Erlotinib is one of the examples of TKIs that has been proven as a successful agent for the treatment of pancreatic cancer or NSCLC (non-small-cell lung cancer) in patients with presumed EGFR mutations. This drug directly inhibits the tyrosine kinase activity of the epidermal growth factor receptor (EGFR) and thus inhibits cancer cell proliferation and survival (Abdelgalil et al., 2020).

Gene Therapy. Genetic mutations underlie diseases, and clustered-regularly-interspaced short-palindrodmic-repeats or CRISPR technology can be used to correct gene mutations in sickle cell anemia (Ma et al., 2023) and cystic fibrosis (Graham & Hart, 2021).

Immunotherapy. This targeted therapy boosts the body's immune system to fight various diseases. For example, pembrolizumab immunotherapy enhances the patient's immune system to detect and attack cancer cells (Cortese et al., 2019).

2. Advancement in drug formulation and drug delivery techniques

Nanotechnology is revolutionizing modern medicine through groundbreaking advances in novel drug formulations and targeted drug-delivery systems. This methodology allows efficient, precise, and targeted delivery of drugs (Abtahi et al., 2024). An overview of how nanotechnology is improving "drug formulation and drug delivery" is presented as follows:

a. Nanoparticles in Drug Delivery

The aim of nanoparticle-based systems is to deliver drugs directly to the target site within the body. This makes the drug more effective and lessens the side effects. Nanoparticles act in drug delivery in numerous ways:

Targeted Drug Delivery. Nanoparticles can be encapsulated with targeting ligands (such as proteins or antibodies) so they can bind to specific cells or tissues (such as cancer cells). This delivery method ensures accurate, direct delivery of a drug to the target tissue without damaging healthy tissues. Doxil, a chemotherapy drug in a liposome shell (a sort of nanoparticle), is such an example. These liposomes selectively bind to and deliver the drug to cancer cells while minimizing damage to healthy cells and maximizing therapeutic drug action (Gabizon et al., 2003).

Controlled Release. The drug can be made to release in a controlled, sustained manner by designing the nanoparticles, thus enhancing bioavailability and maintaining even pharmacological levels of activity while minimizing dosing frequency. Some ongoing developments include the development of nanoparticle-based insulin delivery systems that will allow continuous, controlled insulin release in diabetic patients and eliminate the need for daily injections (Sharma et al., 2015).

Enhanced Solubility and Bioavailability. Drug solubility and bioavailability have always been a considerable challenge in the field of drug discovery because there are certain important drugs that cannot be readily absorbed in the body. Nanotechnology has the potential to resolve this issue, and there has been recent use of certain nanoparticles that can support this front. For example, paclitaxel, a non-soluble chemotherapy drug, is manufactured with the use of nanocrystals to enhance the solubility and absorption, which eventually boosts the bioavailability of this drug (Passos et al., 2023).

b. Nano-machines in Drug Delivery.
Nano-machines are molecular, or nanoscale devices programmed to perform functions at the nanoscale, for instance, delivering medications in response to external triggers or internal biological conditions. These molecular devices can be highly specified to act with great precision in the body (Toumey, 2017).

Stimuli-Responsive Drug Delivery. Nano-machines are highly sophisticated and can be programmed to release medicine only when they are exposed to targeted stimuli, such as changes in pH or temperature, or when a specific molecule or particular enzyme is present. Hence, researchers can design pH-sensitive nano-machines that release their therapeutic payload when they encounter the required acidic environment. This nano-machine property makes them an ideal candidate for the delivery of antitumor drugs, as tumor cells generally have a more acidic pH than healthy cells (Ding et al., 2022).

DNA-based Nano-Machines. DNA can be used to develop nano-machines that deliver the drug. Most DNA machines function by opening or closing in response to molecular signals and thereby control the location and timing of drug (or drugs) release. For example, work has been done to build DNA nanobots that can deliver chemotherapeutic drugs to cancer cells. These are structurally designed to open only upon detecting specific markers on cancer cells (Song et al., 2013).

c. Nano-bots in Drug Delivery.
Nano-bots are an important domain of ongoing nanotechnology advancements, and they are successfully demonstrating that small nano-machines can be effectively used to execute complex tasks at the molecular level. Nano-bots navigate through the bloodstream to target specific cells or tissues, thereby delivering a precise amount of drug to the exact sites of action, minimizing toxicity and improving drug efficacy (Rai et al., 2022).

Bloodstream Navigation. As mentioned above, nanobots use the bloodstream to reach their target organ or tissue (e.g., the site of infection or tumor cells). These nanobots have sensors that help them identify specific markers on the target cell, then deliver a precise payload to it (Li et al., 2017). Near future, these nanobots will be commercially used to treat infections by targeting specific viruses or bacteria. Moreover, as these nanobots can deliver effective doses of the drug to their target cells, this will also help limit the potential for drug resistance.

Minimally Invasive Procedures. Nano-bots could also be used in minimally invasive surgical procedures. These bots can deliver drugs directly to tissues or organs without the need for conventional surgery (Li et al., 2017). Additionally, nanobots can be used in gene therapy that targets tumor sites rather than conventional radiation or chemotherapy.

d. Benefits of Nanotechnology in Drug Delivery.
Targeted Therapy and Reduced Side Effects: The major advantage of nano-bots and nano-machines is the targeted delivery of drugs to specific sites, which provides an alternative to systemic therapy and reduces drug toxicity to healthy cells (Chehelgerdi et al., 2023). This makes the nanotechnology a far better choice in comparison to conventional drugs like chemotherapy. Abraxane is a nanoparticle-based drug for treating breast cancer comprising nanoparticle-conjugated paclitaxel blended with albumin nanoparticles. This combination delivers the drug more effectively to cancer cells by conjugating it to albumin nanoparticles, thereby minimizing side effects (Abu Samaa et al., 2019).

Enhanced Efficacy of Drugs. Nanotechnology can be employed to enable swift delivery and increased bioavailability of various therapies, thereby improving the treatment of medical conditions (Patra et al., 2018).

Personalized Treatment. Nanotechnology enables the development of personalized treatments, as nanoparticles can be engineered to deliver specific drugs, address specific diseases, or meet specific patient needs (Zhou et al., 2020).

Non-invasive Delivery. Some nano-based systems provide an alternative to invasive delivery methods, using approaches such as nano-patches or oral medications that could eventually result in better patient compliance (Khorasaninejad et al., 2013).

e. Future Perspectives in Nano-Drug Delivery Systems
Cancer Treatment. Cancer treatment using nanodrug delivery systems targets only tumor cells, minimizing side effects and sparing healthy cells (Abu Samaa et al., 2019), which is extremely beneficial for cancer treatment.

Gene Therapy. Compared with conventional gene therapy, nanotechnology can deliver genetic material (DNA or RNA) into specific target cells (Ren et al., 2023).

Smart Drug Delivery Systems. Soon, intelligent drug delivery systems, supported by smart nanoparticles, will efficiently respond to diverse cellular environments (pH, temperature, or specific biomarkers). This feature of nanoparticles will pave the way for full control of targeted drug delivery to specific locations as needed (Abtahi et al., 2024).

With the deployment of nanotechnologies (nanoparticles, nano-machines, nano-bots), the accuracy and precision of the drug delivery systems can be significantly enhanced, and side effects of the drugs can be minimized, which will provide a new hope for the better treatment of different infectious diseases, genetic diseases, and cancers (Li et al., 2023). The incorporation of nanotechnologies will transform the entire medical industry, from drug discovery, formulation, and delivery, to providing smarter, more innovative treatment options for currently incurable diseases. Ongoing research and development in nano-medicine and nanotechnology will provide additional novel breakthroughs in drug delivery and treatment.

3. Regenerative Medicine: Transformation of Modern Medicine
Regenerative medicine is a very important discipline of modern medicine that plays a critical role in restoring the normal functions of any damaged tissues or organs by improving the natural process of repair, replacement, and regeneration. In regenerative medicine, principles of engineering and biology are incorporated to develop new therapies for treating incurable diseases. This unique front of modern medicine has introduced several alternative options (discussed below) to conventional treatments, like prosthetic devices and transplants (McKinley et al., 2023).

Significance of Regenerative Medicine

1. Stem Cell Therapy

Stem cells have the unique property of regenerating into a variety of cell types and are self-renewing. Therefore, stem cell therapy offers new hope for treating various diseases. For example, in cardiology, stem cell therapy can be employed to regenerate damaged myocardial tissue after a heart attack. For example, in cardiology, mesenchymal stem cells (MSCs) derived from bone marrow show cardiomyogenic potential by regenerating damaged heart muscle and restoring heart function (Ding et al., 2011). Stem cell therapies also promote regeneration of bone and periodontal structures around teeth affected by periodontitis. Stem cell therapy has also been investigated for the regeneration of dental pulp (Masuda et al., 2021).

2. Gene Therapy

Gene therapy is the correction or replacement of defective genes to treat chronic or genetic disorders. This technique is one of the key approaches in regenerative medicine that targets specific cells, altering the function of certain genes to facilitate healing. For example, in hemophilia, gene therapy is used to replace defective clotting factors, significantly reducing patients' recurrent transfusion requirements (Nathwani, 2022). A similar effective approach in dentistry is the use of gene therapy (uterine sensitization-associated gene-1), which activates specific genes that support the regrowth of dental tissues (Murashima-Suginami et al., 2021).

3. Platelet-Rich Plasma (PRP) Therapy

To promote healing and repair in a patient, PRP therapy uses platelets derived from the patient's blood, which are rich in growth factors that stimulate healing. PRP injections offer a novel therapeutic approach in sports medicine to treat osteoarthritis, ligament tears, and tendon injuries (Hada et al., 2024). In dentistry, PRP therapy is used to enhance bone healing after tooth extraction and to improve success rates in dental surgery (Rutkowski et al., 2010).

4. 3D Bioprinting

This technology uses bio-inks derived from live cells to print tissues and organs layer by layer, creating the closest possible natural biological structures. These innovative bioprinting techniques are not only used by scientists to produce "3D printed skin grafts" for burn victims, but also to bioprint organs, such as livers and kidneys, for transplantation (Murphy & Atala, 2014). Likewise, in dentistry, 3D bioprinting is being researched for generating customized Jaw-bone structures to treat patients with severe facial injuries (Liu et al., 2015).

Hence, regenerative medicine will introduce novel concepts into modern medicine through innovative solutions for regenerating tissues and organs, thereby significantly improving the entire healthcare system. Due to improved clinical outcomes, there will be less demand for organ donations, and quality of life will be improved. Additionally, as technology and research advance, regenerative medicine will be a cornerstone of future precision and personalized medicine.

4. Bioengineering: Revolutionizing Modern Medicine and Dentistry

Bioengineering, or biomedical engineering, encompasses principles from engineering and the biological sciences, offering countless opportunities for innovation in medical research and the advancement of therapeutic knowledge (Tsouknidas, 2024). Bioengineering is one of the main cornerstones of modern medicine, which facilitates improvements in diagnostics, therapeutics, and regenerative medicine.

General Features of Bioengineering and Their Applications

a. Medical Imaging and Diagnostics. Bioengineering has led to the development of cutting-edge imaging technologies that are playing a key role in early disease detection and improving patient care. The concepts of bioengineering have steered towards the production of high-resolution images of internal organs through computed Tomography (CT) scans and Magnetic Resonance Imaging (MRI), which are very crucial in the diagnosis of certain diseases that require urgent attention, such as cancer, stroke, and some neurological conditions (Hendee et al., 2008). Likewise, in dentistry, Cone-Beam Computed Tomography (CBCT) is used to acquire comprehensive 3D images of dental structures and the jaw, enabling swift and accurate implant positioning and orthodontic therapeutic planning (Fu et al., 2024).

b. Prosthetics and Bionic Limb.: Bioengineering has been a main contributor in transforming prosthetic technology and has led to the development of sophisticated functional artificial limbs, which effectively support amputees to gain their normal or improved mobility and refine their quality of life. Bioengineering has also supported the development of bionic arms and legs equipped with neural interfaces, allowing amputees to control them with their brain signals as normal (Radeleczki et al., 2023). Similarly, in dentistry, dental prosthetics such as bridges, crowns, and dentures are customized using 3D printing, a bioengineering technique that offers personalized solutions for patients (Schweiger et al., 2021).

c. Biomaterials and Tissue Engineering. Recent innovations in biocompatible materials are playing a vital role in the manufacturing of various artificial organs, implants, and grafts. Biomaterials such as titanium and biopolymers are used to implant several tissues, including heart valves and vascular grafts, which replace necrotic tissues in patients with damaged cardiac tissue. Similarly, in dentistry, jawbone tissue is restored by using hydroxyapatite scaffold-based bone graft materials before placing a dental implant in maxillofacial or oral surgery (Ma et al., 2017).

d. Wearable and Implantable Medical Devices. The combination of wearable technologies and implantable devices enables real-time health assessment and enhances personalized medicine. For instance, smart insulin pumps can precisely deliver insulin to diabetic patients, improving diabetes management. Likewise, modern pacemakers can manage cardiac rhythms instantaneously and can reduce disease burden for cardiovascular patients. Similarly, in dentistry, sophisticated dental implants are used to provide real-time monitoring of oral health conditions, implant stability, bone loss, and infection (Gao & Yu, 2021).

Bioengineering is redefining the outlook of modern medicine and dentistry through its innovative approaches for diagnostics, regenerative therapies, and treatment modalities for different diseases (Landau et al., 2024). Recent advancements in bioengineering, ranging from imaging science to prosthetics and 3D printing, are reshaping and shifting the future of healthcare. Recent discoveries in bioengineering are expected to improve surgical and medical outcomes, paving the way for enhanced standards of medical care, personalized medicine, and improved quality of life.

5. Artificial Intelligence and Machine Learning in Drug Development and Healthcare

In this review, AI is treated as a broad family of systems that augment human intelligence and decision making, while ML is presented as its data-driven analytical core that learns patterns from large health datasets to generate predictions and recommendations. The recent implementation of AI and ML in medicine and dentistry is offering cutting-edge therapies by expediting drug discovery, refining medical diagnostics, and optimizing treatment planning, thereby improving standards of patient care (Sahu et al., 2022). AI and ML are leveraging advanced computational methods to accelerate the analysis of large medical datasets and enable deep learning (Kayama et al., 2021). These methodologies are resulting in accurate diagnoses of different diseases, supporting the advancement of personalized treatments and ultimately improving the standards of the healthcare system.

a. AI and ML-based Drug Discovery Hyper-personalization in Healthcare.

Drug Discovery is a very expensive and exhaustive process, and sometimes takes ages to discover a new drug. AI and ML have the technical capability to significantly shorten this span by scanning a substantial body of available research data, identifying potential drug candidates, and estimating the efficacy of new drugs (Jiménez-Luna et al., 2021).

Applications in Drug Discovery

Target Identification and Validation.

AI and ML models can support the identification of different molecular targets for a drug by analyzing genetic and molecular data for a specific pathogen (e.g., proteins involved in cancer).

Discovering a New Generation of Drugs.

AI and ML technologies can fast-track drug discovery by intelligently selecting potential candidates for the new generation of drugs by predicting their molecular interactions.

Drug Repurposing.

AI has the operational abilities to analyse the current drug database comprehensively and can unearth additional therapeutic uses of available medicines for other diseases. Recent AI scanning of available drug data has identified baricitinib, used to treat arthritis, as a potential candidate for treating COVID-19 (Richardson et al., 2022).

b. AI in Diagnostics

Diagnostic tools powered by AI deliver faster execution, greater precision, and earlier disease diagnosis. Google's DeepMind Health is an example of the practical application of AI in ophthalmology diagnostics. This AI tool can rapidly analyze eye scans to diagnose diabetic retinopathy, potentially facilitating early diagnosis and treatment of conditions linked to blindness (Masalkhi et al., 2024).

Diagnostic Application

Medical Imaging. AI interprets X-rays, CT scans, and MRI images with high precision, facilitating early detection of diseases and conditions such as tumors and fractures.

Pathology & Cancer Detection. Computational models powered by AI expedite molecular-level diagnostics, enabling the identification of cancer cells at a significantly faster pace than conventional methods (Topol, 2023).

Genomic analysis. Large genomic datasets are efficiently processed by AI, which supports the identification of hereditary predisposition to diseases such as diabetes and Alzheimer's disease (Ellahham, 2020).

c. AI Changing Treatment Planning and Personalized Medicine

AI technology is one of the main pillars of personalized medicine, supporting physicians and dentists in formulating customized treatments and adjusting therapies based on patients' genetic profiles, lifestyle factors, and medical histories. Additionally, the application of AI-enabled technologies is helping oncologists determine precise radiation doses for cancer patients, thereby minimizing toxicity to healthy cells. For instance, the use of IBM Watson Health's AI helps physicians make strategic decisions by scanning patient records alongside available medical literature. This technology not only facilitates the diagnosis of different types of cancer but also integrates clinical and genomic data to recommend the most effective personalized cancer therapies (Jiang et al., 2017).

d. AI and Machine Learning in Patient Care & Digital Health

AI and Machine learning technologies are transforming remote patient monitoring, service delivery, and medical care. AI technologies are becoming increasingly popular in inpatient care, and various chatbots are serving as virtual health assistants, supporting early diagnosis, offering medical recommendations, and scheduling medical appointments. Additionally, the health status of any patient can be remotely monitored through AI-enabled platforms that can easily detect abnormal changes in a person's physical parameters and send alerts to their physician.

AI-powered smartwatches and fitness trackers can continuously record blood pressure, pulse rate, and sleep patterns, helping individuals continuously monitor their symptoms and identify any signs of illness in a timely manner. For example, ECG-enabled Apple smartwatches equipped with AI can identify cardiac rhythm abnormalities, and this data can be continuously shared with their physician. This approach not only allows remote monitoring of patients but also supports the formulation of various prophylactic therapies to prevent conditions such as strokes and cardiac pathologies (Prieto-Avalos et al., 2022).

e. Digital Health Innovations Complementing Drug Therapies

AI development, along with advancements in smart devices and digital eHealth tools, is projected to enhance the impact of modern drug therapies. Recently, Propeller Health (a digital therapeutic company) has introduced AI-based inhaler sensors that are connected to the smartphone of the patient. This tool can detect environmental triggers for different respiratory diseases, provide patients with guidance on their medication, and contribute to improved treatment outcomes (Merchant, 2016).

AI-based drug adherence apps are also being introduced in the healthcare industry, which alert patients about their regular medications and analyze the impact of missed doses. Hence, these apps are improving medication adherence through regular reminders to patients (Merchant, 2016). Likewise, AI-powered applications are also being introduced in clinical trials, capable of analyzing patient data across hospitals and optimizing the identification of patients who meet the inclusion/exclusion criteria of any new clinical trial. Thus, increasing patient recruitment for clinical trials and supporting effective testing of novel drugs.

AI and ML mark the beginning of a new era in healthcare with optimization in diagnostics, advancement in drug discovery, refinement in treatment planning, and improved patient care. With ongoing innovations in technology-enabled healthcare, their contributions to enhancing drug efficacy would advance personalized and affordable medicine (Ryan et al., 2024). The future of medicine is evolving towards integration with AI, opening new avenues for personalized medicine and patient-centered care.

6. Digital Health: Reforming Contemporary Medicine and Dentistry

Digital healthcare technologies include smart wearable devices, different health apps, eHealth records, etc. These cutting-edge tools are facilitating disease diagnosis, treatment, prevention, and patient management, by which the healthcare will become more precise, personalized, efficient, and accessible (Ginsburg, 2024).

a. Wearable Devices in Healthcare. These devices support continuous monitoring of key physiological parameters in susceptible individuals, enabling early disease detection and effective patient management.

Applications in Medicine and Dentistry
Cardiac Monitoring. Abnormal cardiac rhythms or potentially fatal heart conditions can be tracked by modern smartwatches equipped with ECG sensors. Hence, these devices can contribute towards the prevention of high blood pressure and stroke (Perez et al., 2019).

Management of Diabetes. Diabetic patients can benefit from using continuous glucose monitors (CGMs), which continuously monitor glucose levels and send alerts and insulin recommendations (Diez Alvarez et al., 2024).

Bruxism Monitoring. Teeth grinding (Bruxism) in an individual can be monitored using mouthguards shaped like teeth that contain an auxiliary sensor coating. These sensors are wirelessly connected with smartwatches and send notifications to take preventive measures (Velásquez et al., 2022).

Tracking Oral Hygiene. Smart toothbrushes connected to mobile phone apps can monitor individuals' brushing habits and provide feedback, which can be used to enhance their oral hygiene.

b. Mobile Health Applications for Personalized Healthcare

Mobile Health (mHealth) apps are efficient tools in the modern world that empower patients to self-monitor and manage their health conditions. mHealth apps support the following areas of medicine and dentistry.

Telemedicine applications. mHealth apps support online consultations with doctors, nurses, and allied health workers for patients who are unable to attend in-person appointments or need urgent care. Additionally, telemedicine is playing a key role in limiting the spread of infectious diseases by reducing hospital visits.

Mental health support. Different mHealth applications support the scheduling of remote therapy sessions, stress tracking & management, and meditation facilitation. For example, the BetterHelp portal provides AI-integrated therapy and psychological support, which helps enhance patients' mental health (Marcelle et al., 2019).

Orthodontic Monitoring and Teledentistry applications. Several AI-based mHealth apps are used in orthodontic monitoring to track the progress of braces and Invisalign treatments remotely. Similar apps are also facilitating the scheduling of virtual initial consultations and follow-ups with dentists, thereby reducing the burden of in-person appointments. For example, with the SimpleDirectClub app, patients can monitor the progress of their orthodontic treatment at home, and the same data can be shared in real time with their dentist (Zweihorn, 2022).

c. Electronic Health Record (EHR)
EHR is a computerized system for recording and organizing patient health data in a structured manner, supporting coordination among healthcare providers.

Applications in Medicine and Dentistry
Real-Time Data. Doctors can automatically access patient history, test results, and final treatment plans. Likewise, in dentistry, patients' records, including radiographs, treatment history, and periodontal health, are electronically stored to support patient treatment (Layman, 2020).

AI-Driven Diagnostics. Integration of AI into EHRs allows disease pattern detection and risk forecasting. For example, Epic Systems combines AI into EHRs to predict sepsis risk among hospitalized patients (Tan et al., 2024).

Insurance and Billing Automation. The EHR improves the claims process and makes appointment scheduling easier. Dentrix is a widely accepted dental EHR system, which improves the efficiency of a clinic (Thyvalikakath, 2020).

d. AI and Big Data Convergence in Digital Health
Digital health-based artificial intelligence analytics support personalized medicine and predictive medicine. For example, Google DeepMind's AI translates retinal scans to detect eye diseases like diabetic retinopathy before symptoms manifest (Masalkhi et al., 2024).

Digital health technology, such as wearables, health apps, and EHRs, is transforming contemporary medicine and dentistry. They are improving patient monitoring, simplifying diagnostics, and improving treatment. As the evolution continues, digital health will play a more crucial role in preventive care and precision medicine.

7. Telemedicine/Teledentistry: Transforming Modern Healthcare

The practice of telemedicine/teledentistry has significantly evolved, transforming modern healthcare systems by delivering medical and dental services via digital communication. Telemedicine/teledentistry allow patients to consult healthcare experts for diagnosis and treatment remotely, without visiting a clinic or hospital in person. The application of such technologies makes healthcare more accessible, cheaper, and better for the patients (Waller & Stotler, 2018). Whether it is chronic disease management or the complications of acute diseases, telemedicine minimizes the need for inconvenient hospital visits and alteration of long-standing doctor-patient relationships. For example, any individual suffering from a minor illness, such as an allergy or the common flu, can arrange a remote appointment with a health professional, freeing a slot for an in-hospital appointment for a person with a more serious condition. Likewise, medical conditions, such as chronic diseases like high blood pressure, cardiovascular illness, and diabetes, can be tracked and managed remotely (Wolf et al., 2022).

With the rapid advancements in telemedicine, large numbers of mobile apps and wearable devices are being introduced, offering real-time healthcare oversight through instantaneous data transmission to remote medical facilities. For example, wearable ECG monitors help transmit heart rate data to physicians, enabling early detection of arrhythmias (Prieto-Avalos et al., 2022). Smart glucometers can be integrated with telemedicine platforms, enabling physicians and patients to adjust insulin doses remotely (Ellahham, 2020). Telemedicine also has an important additional advantage: improving healthcare accessibility in remote and underdeveloped rural areas by enabling remote access to healthcare specialists. For instance, through telemedicine, an emergency team based in distant areas can remotely consult a neurologist to seek urgent support for a person with a stroke. It also provides mental health services by allowing patients in remote locations to access virtual therapy and psychiatric care.

In teledentistry, patients experiencing varying degrees of dental pain, gum infections, or braces-related concerns can consult a dentist through a tele-oral health program prior to scheduling an in-person visit (Howell & Fukuoka, 2022). Post-treatment follow-ups can also be performed from the comfort of home, allowing dentists to monitor an individual's recovery after tooth extraction or implant procedures. Using AI-powered apps, dentists can analyse images of braces or Invisalign aligners without the patient needing to come in for an office visit. Smart toothbrushes, then, can help the patient track their brushing habits. Emergency dental support through telemedicine helps patients manage severe toothaches or trauma until they can get in-person treatment. Additionally, it enables rural patients to consult dental specialists, such as endodontists or periodontists, without long-distance travel (Batra et al., 2022).

Telemedicine and teledentistry have not only increased access to care but also saved by reducing costs associated with hospital traffic, travel, and care delivery (Gentili, 2020). AI further amplifies telemedicine/teledentistry by analyzing patients' data with algorithms to predict health risks and recommend preventive care strategies. In short, telemedicine and teledentistry are changing the face of healthcare delivery by improving accessibility, reducing costs, and delivering a broader range of better patient outcomes (Batra et al., 2022; Waller & Stotler, 2018). By virtue of their applications in remote consultations, chronic disease management, emergency care, and AI-oriented diagnostics, telemedicine and teledentistry are becoming increasingly relevant to what both medicine and dentistry offer today. With the advancement in technology, telemedicine and teledentistry will remain integral to personalized and preventive healthcare.

Practical Utilization of AI in Clinical Diagnostics – The Case of EndoBRAIN

Recent advancements in Artificial Intelligence, which extend far beyond theoretical constructs and are now within the province of active clinical diagnostics, are recent advancements. This has recently been demonstrated in colorectal cancer detection with the EndoBRAIN series, developed in Japan. Using high-resolution endocytoscopic images and high precision, the facility can readily distinguish neoplastic from non-neoplastic lesions. It has been documented that EndoBRAIN achieved diagnostic accuracy of approximately 98% (Kudo et al., 2019). With its latest version of EndoBRAIN-X being approved for standard colonoscopy, the product has emerged as a champion in its applicability.

One Health Connects with Artificial Intelligence

One emerging trend in biomedical sciences is understanding the interface among human, animal, and environmental health. This was highlighted during the COVID-19 pandemic, which triggered a deeper understanding of the interrelationships among these components. This led to enhanced collaboration among health scientists, physicians, dentists, veterinarians, and environmental health advocates. Advances in artificial intelligence were leveraged to design diagnostic tools that can be useful even in the context of supporting One Health perspectives. Gene synthesis technologies, PCR- and LAMP-based detection, and AI-driven bioinformatics are now redefining how we predict, monitor, and prevent disease outbreaks for zoonotic and environmentally linked infections (Camer et al., 2003; Camer et al., 2008; Camer et al., 2010; Camer et al., 2012; Camer et al., 2019; Sleem et al., 2024; Kayama et al., 2021; Endoh et al., 2024). The following advancements, albeit not yet developed into a readily available AI-utility App, have the potential to be converted into AI and machine learning tools to assist scientists, clinicians, and researchers in fast-tracking molecular-based enterprise applications.

Artificial Gene Synthesis that Supports One Health Initiatives

To address the threat of the next global pandemic, an algorithmic overlap extension polymerase chain reaction (OE-PCR) was developed to generate novel synthetic nucleotides for notifiable dengue (types 1-4), Zika, Japanese encephalitis, and other flaviviruses. These are world-renowned diseases listed as major threats to human and veterinary health (Camer et al., 2019; Camer et al., 2020). The algorithmic OE-PCR design is available online for peer scientists to use (https://rb.gy/tkxvm9). This could be enhanced into an AI-algorithmic design that leverages the need for synthetic DNAs. With the expansion of another synthetic gene formulation platform, the production of artificial genes was made compliant with the need for larger sizes of synthetic DNA products, where the latest has enabled the production of greater than 1kB of synthetic nucleotides ready for immune-research explorations (Kayama et al., 2021; Nishida et al, 2023). These methods were further enhanced by recurrent neural networks of ML applications (Kayama et al, 2021).

Inevitably, the use of synthetic DNAs is invaluable, particularly in the fields of medicine, veterinary medicine, and public health, as it can readily handle potentially hazardous and zoonotic pathogens of highly pathogenic avian influenza (HPAI), foot and mouth disease (FMD), and notifiable dengue, Zika, and other flaviviruses (Camer et al, 2020). These advancements help ensure the resounding success of One Health initiatives, enabling everyone to benefit from prompt disease detection and epidemic prevention.

Development of Machine Learning Models in LAMP Amplification Prediction

Increasingly adopted are quicker molecular diagnostic tools that could expedite disease diagnoses of animal, human, and ecological origins. Isothermal amplification techniques, such as LAMP, are increasingly adopted for their simplicity and field adaptability. While many scientists use LAMP as a readily adaptable technology, the pitfall of this isothermal method is the emergence of high false-positive results, thereby compromising its diagnostic accuracy. To this end, ML model has been developed to improve the complex interactions between primer and template sequences. It involved incorporating new ML, including AutoML simulation pipelines that could provide improved predictive accuracy for LAMP (Sanekata et al., 2024; Endoh et al., 2024). These recent models, which incorporated 1,512 primer-template alignment settings and were evaluated using F1 scores, have achieved up to 0.721 in sensitivity and 0.84 in accuracy at 68°C isothermal conditions (Endoh et al., 2024).

Importantly, these models also used artificial gene templates synthesized from the V8 region of bacterial 16S rRNA genes, exemplifying how artificial gene synthesis supports ML in diagnostics (Sanekata et al., 2024). Such systems are pivotal in a One Health context, enabling field diagnostics for zoonotic diseases at the human–animal–environmental interface. Table 5 synthesizes the key technologies discussed—highlighting how artificial intelligence, machine learning, nanotechnology, and bioengineering contribute to diagnostics, therapeutics, and health surveillance within the modern healthcare ecosystem."

Machine Learning and Recurrent Neural Networks for PCR Success Prediction

Another groundbreaking innovation is the use of recurrent neural networks (RNNs) to predict PCR amplification outcomes. This ML method transforms primer-template pairs into pseudo-sentences that RNNs can process in a manner like natural language, learning from over 3,900 PCR trials (Kayama et al., 2021). The success of this AI-based design has been lauded for attaining a 70% accuracy, a percentage that surpassed the usual thermodynamic protocols and even the traditional designs for ensuring better DNA product bonds with higher GC-content. All these are contributing to improved accuracy in molecular diagnostics.

In upholding One Health, the development of pathogen-specific analyses, such as those enabled by advances in AI and machine learning, is critical. Hence, the AI-modelled prediction can assist in developing an expedited, temporal, and primer-specific pathogen diagnostic tool, such as those urgently needed for epidemic and epizootic outbreaks (Table 4).

Table 4: Applications of AI, ML, Nanotechnology, and Bioengineering in Modern Healthcare
Section A: Artificial Intelligence and Machine Learning Across Healthcare Domains

Healthcare Domain	AI/ML Applications	Examples/Tools
Drug Discovery	Target identification, drug repurposing, and molecular simulation	Baricitinib for COVID-19, DeepMind for molecule screening
Diagnostics	AI-assisted imaging (X-ray, CT, MRI), cancer detection, genomic analysis	DeepMind Health for diabetic retinopathy
Treatment Planning	Customized therapies, radiation dose calculation, IBM Watson for oncology	IBM Watson Health, Deep learning in radiotherapy
Patient Monitoring	Wearable devices, smart alerts, predictive patient deterioration monitoring	Apple ECG watch, Dexcom G6 glucose monitor
Digital Health	Mobile apps, EHR integration, chatbot triage systems	Propeller Health, SmileDirectClub, Epic Systems EHR
One Health Surveillance	PCR/LAMP optimization, synthetic gene design, zoonotic outbreak prediction	AI models for OE-PCR and RNN-based PCR prediction

Section B: Nanotechnology and Bioengineering Contributions to Healthcare

Technology	Purpose	Benefits
Nanoparticles	Targeted drug delivery, controlled release, enhanced solubility	Reduced toxicity, better efficacy
Nano-machines	Stimuli-responsive drug release, DNA nanobots	On-demand release, specific to the disease environment
Nano-bots	Precision navigation in the bloodstream, minimally invasive drug/gene delivery	Improved targeting, reduced systemic exposure
Bioengineering (Prosthetics)	Advanced bionic limbs, dental prosthetics with neural interfaces	Restores mobility and oral function, enhances life quality
Bioengineering (Imaging)	High-resolution CT/MRI, dental CBCT imaging	Early disease detection, planning precision EndoBrain
Bioengineering (3D Printing)	Bioprinted skin grafts, dental jaw reconstructions	Customized, regenerative solutions for tissue loss

Synergistic AI-based Platforms and One Health

The advent of AI and machine learning in making diagnostics readily accessible not only supports the further sophistication of the medical and dental industry but also the need to respond to growing concerns about the interplay among human, animal, and environmental health. Formulating synthetic DNA using AI-driven platforms supports the development of novel synthetic DNA-based immunogens. It is noteworthy that the use of AI-developed nucleotides could further scale up the vaccine industry without the risk of handling highly pathogenic and hazardous bacterial and viral species that may spill and threaten public health (Camer et al., 2019; Nishida et al., 2023; Kayama et al., 2021).

Future of AI in Health Informatics – Meta-AI via Model Context Protocol (MCP)

As medical health information matures through the advent of AI, there tends to be a paradigm shift from isolated, task-specific models to meta-AI frameworks that can adaptively select, organize, and improve compound AI drivers based on task context. Pivotal to this progression is **MCP**, a novel agent-based design gaining traction across the broader AI industry (Figure 2). MCP facilitates the integration of software mediators with distinct programs such as ChatGPT, Gmail, and health information systems to enable context-aware, multi-source analysis and decision-making. This novelty aligns proximally with meta-learning, or the concept of "learning to learn". This helps AI systems promptly adapt in scenarios characterized by data scarcity, domain shifts, and growing concerns in clinical informatics (Rafiei et al., 2024; Khadse et al., 2025). These approaches can boost performance by selecting the most efficient AI models for specific medical parameters, such as disease prognosis, diagnosis, and treatment regimen recommendations (Figure 3; Table 5).

Table 5: Key AI Innovations in Health Information Ecosystems: Methods, Purposes, and Implications

Innovation	Method / Framework	Purpose / Highlights
PCR Success Prediction via RNN	Primer-template sequences transformed into "pseudo-sentences" for Recurrent Neural Network learning (approx. 3,900 trials, ~70 % accuracy)	Predicts PCR amplification outcomes more accurately than traditional thermodynamic designs; facilitates rapid, data-driven primer design for molecular diagnostics
Synergistic AI Platforms & One Health	AI-driven generation of synthetic DNA (e.g., immunogens) via ML platforms—eliminates the need to handle pathogenic agents directly	Supports scalable, safe vaccine and diagnostic development across human, animal, and environmental health domains
Meta-AI via Model Context Protocol (MCP)	Agent-based meta-AI framework using MCP to orchestrate multiple context-aware AI tools (model context protocol enables standardized connectivity between AI systems and tools)	Enables adaptive "learning-to-learn" AI—selects optimal models per task, responds to data scarcity and shifting domains, improves decision-making in evolving clinical contexts

Visual Synthesis of AI, ML, and Data Science Across Health Ecosystems

In **Figure 3**, AI is presented as an overarching ecosystem encompassing a broad range of intelligent systems, including robotics, automation, decision-support tools, and emergent frameworks such as meta-AI and MCP. ML is positioned as the analytical engine of AI, providing the data-driven learning algorithms that enable pattern recognition, prediction, optimization, and decision-making. Data Science is shown as the application space where ML tools are operationalized to generate insights across diverse contexts. The diagram also links these three layers to the key use-case ecosystems discussed in this review—Health Information Systems, One Health surveillance, and Bioengineering—highlighting their interdependencies and shared reliance on AI-enabled analytical workflows. This visual synthesis provides readers with an integrated conceptual framework that unifies the technical and applied dimensions presented throughout the manuscript.

Contextual Challenges of AI/ML Implementation in Developing Countries

Developing countries such as the Philippines and several ASEAN nations face significant structural and contextual barriers that influence the adoption of AI and ML in health, One Health, and bioengineering systems (Table 6). Physical infrastructure remains uneven, with disparities in computing capacity, internet reliability, and access to laboratory or clinical hardware—challenges repeatedly highlighted in regional digital health assessments (WHO, 2021; Canton, 2021). Digital systems also suffer from fragmented data architectures, limited interoperability, and inconsistent cybersecurity standards, issues that constrain the creation of unified datasets required for robust AI model development. Human resource limitations compound these gaps: the region continues to experience shortages of AI-literate professionals, limited formal AI/ML academic programs, and the outward migration of trained talent, all of which contribute to weak R&D capacity. Policy and governance frameworks are still evolving, with many countries lacking comprehensive AI ethics guidelines, data governance regulations, or inclusive national AI strategies to ensure equitable access to emerging technologies (Lewis et al., 2021; Ziesche, 2023; WHO, 2023). These interconnected challenges, along with the recommended policy solutions proposal (Table 6), underscore the need for coordinated investments in infrastructure, workforce development, and governance systems to ensure AI/ML implementation is both responsible and sustainable in developing-country settings (Qudrat-Ullah, 2025; Quimba et al., 2024).

Table 6. Contextual Challenges and Policy Directions for AI/ML Implementation in Developing Countries, including the Philippines.

Dimension	Current Gaps / Challenges	Recommended Policy Directions
1. Physical Systems (Infrastructure, computing capacity, hardware access)	1. Limited digital and computing capacity **2. Uneven access to connectivity and hardware** 3. Power instability in underserved areas	1. Build a scalable national digital infrastructure 2. Expand equitable access to connectivity and AI hardware 3. Strengthen energy resilience
2. Digital Systems & Procedures (Interoperability, cybersecurity, data standards)	1. Fragmented digital systems 2. Inconsistent data standards 3. Weak cybersecurity readiness	1. National interoperability standards 2. Unified data dictionaries and FAIR standards 3. Strong cybersecurity protocols and audits
3. Manpower & R&D Capacity (Training, workforce development, research funding)	1. Shortage of AI/ML-trained professionals 2. Insufficient funding for AI/ML research and infrastructure 3. Limited accredited training programs and cross-sector collaboration	1. Expand AI/ML degree programs, scholarships, and national training pipelines 2. Establish AI/One Health R&D centers and sustainable research funding 3. Strengthen CPD/microcredentials and foster cross-sector One Health training
4. Policy & Governance (Ethics, regulation, equity)	1. Lack of national ethical AI guidelines 2. Limited incentives for AI adoption in institutions 3. Technological inequity between urban and rural sectors 4. No clear regulatory pathway for AI validation and oversight	1. Develop national AI ethics and governance frameworks 2. Provide incentives and modernization grants for AI adoption 3. Establish regional AI hubs with shared resources 4. Create standardized regulatory pathways for AI approval and monitoring

AI-Driven Development Platforms and the Democratization of AI in Health

Beyond the advanced applications reviewed in this paper, a critical parallel development is the increasing accessibility of AI and ML tools across clinical, veterinary, public health, and bioengineering domains. Historically, creating ML pipelines required substantial programming expertise in Python, R, TensorFlow, or PyTorch. Today, however, AI development spans a continuum—from code-intensive environments to **low-code and no-code platforms**—allowing broader participation among clinicians, dentists, veterinarians, and other domain experts.

At the code-intensive end, open-source ecosystems such as Python and R remain essential for customized model development, interpretability analysis, and integration with omics, drug discovery, biomarker analysis, nanomedicine modeling, and high-resolution imaging pipelines (Jiménez-Luna et al., 2021; Sahu et al., 2022; Ryan et al., 2024). These environments support the deep computational tasks central to precision medicine and bioengineering.

In parallel, **no-code and low-code platforms** now enable non-programmers to build ML pipelines using intuitive, visual interfaces. Tools such as Orange allow drag-and-drop workflow construction for data preprocessing, clustering, classification, and evaluation (Demšar et al., 2013; Dobesova, 2024). In medical and dental imaging, AutoML systems have been demonstrated to "democratize" AI by enabling code-free or code-minimal model training and comparison for diagnostic and prognostic tasks (Thirunavukarasu et al., 2023; Scott et al., 2024). Commercial tools such as Google Cloud AutoML Vision explicitly promote accessibility by enabling model training **"without ML expertise"** (Zeng & Zhang, 2020). Healthcare feasibility studies similarly show that even professionals without coding experience can design deep learning classifiers for imaging workflows (Faes et al., 2019; Korot et al., 2021).

Across enterprises and academic settings, **low-code/no-code** AI platforms and AutoML pipelines empower "citizen developers" to construct AI solutions while still enabling specialists to refine and govern these systems (Giraldo et al., 2025; Bagheri et al., 2024). Within health information, One Health, and bioengineering domains, these tools allow:

1. Hospital and public health teams to prototype risk-prediction models using EHR or surveillance datasets;
2. One Health researchers to explore LAMP/PCR or synthetic DNA datasets using visual AutoML interfaces before transitioning to bespoke coded pipelines;
3. Bioengineers to benchmark imaging models, nanodrug designs, or bioprinted-tissue datasets without writing scripts from scratch.

These developments align with emerging **meta-AI** and **Model Context Protocol (MCP)** frameworks, which orchestrate diverse AI systems—some code-based and others no-code—into a unified, context-aware decision-support ecosystem for clinicians, veterinarians, and environmental health professionals.

Integrated Schema of AI-Driven Innovations in Modern Healthcare

To integrate these diverse domains into a coherent perspective, the following conceptual schema summarizes how AI, ML, bioengineering, nanotechnology, precision medicine, digital health, and the One Health paradigm interact as components of a single, unified healthcare ecosystem.

1. AI-Driven Diagnostics
   AI now plays a central role in accelerating and refining diagnostic accuracy across medicine, dentistry, and veterinary practice. Its applications include AI-assisted imaging modalities such as X-ray, CT, MRI, and CBCT; automated endoscopic lesion recognition; digital pathology for early cancer detection; and genomic interpretation systems that support biomarker-based decision-making. By enabling earlier and more precise disease identification, these AI-driven diagnostic platforms significantly enhance clinical decision-making and patient outcomes.

2. Telemedicine and Teledentistry
   AI-enabled telemedicine and teledentistry have expanded access to healthcare by enabling virtual consultations, automated triage systems, remote monitoring of chronic conditions, and continuous assessment using AI-enhanced wearable devices, such as ECG and glucose sensors. These technologies also enable remote dental and orthodontic evaluations that previously required in-person visits. Collectively, these innovations improve continuity of care, particularly for geographically isolated, aging, or underserved populations.

3. One Health: Integrated Human–Animal–Environment Health
   The One Health framework recognizes the intrinsic interconnectedness of human, veterinary, and environmental health. AI contributes to this paradigm by enabling zoonotic outbreak prediction, optimizing PCR and LAMP diagnostic workflows, and supporting synthetic gene design without directly manipulating high-risk pathogens. AI-based ecological and environmental monitoring further strengthens biosurveillance systems, thereby improving global preparedness for emerging infectious diseases.

4. Bioengineering Innovations
   Bioengineering is rapidly transforming therapeutic strategies and rehabilitative interventions. Advances in this domain include 3D bioprinting of skin, bone, and dental structures; development of bionic prosthetics equipped with neural interfaces; tissue engineering and regenerative medicine approaches; and the use of smart implants guided by imaging analytics. AI enhances these innovations by improving biomaterial modeling, optimizing bioprinting parameters, and supporting personalized treatment planning.

5. Nanotechnology-Enabled Drug Delivery
   Nanotechnology contributes to precision therapeutics by enabling targeted drug delivery systems, nanoscale machines responsive to biological cues such as pH and temperature, and DNA-based nanostructures designed for cancer-specific targeting. These nanomedicine platforms improve pharmacokinetic profiles, minimize toxicity, and enhance therapeutic efficacy. When integrated with AI-driven optimization and predictive modeling, nanotechnology becomes a powerful tool for personalized and controlled treatment strategies.

6. Precision and Personalized Medicine
   AI supports precision medicine by integrating genomic, clinical, behavioral, and environmental datasets to predict disease susceptibility, forecast treatment responses, guide pharmacogenomic decisions, and design individualized therapeutic pathways. This data-driven approach shifts healthcare from reactive treatment toward proactive, predictive, and preventive intervention, aligning with emerging standards of precision health.

7. Meta-AI and the Model Context Protocol (MCP)
   Meta-AI, operationalized through MCP, represents an emerging phase in AI evolution wherein multiple AI systems—diagnostic, genomic, environmental, and robotic—are orchestrated into a coherent upper-layer architecture. MCP selects the most context-appropriate model for each decision scenario and enables adaptive, real-time decision support even in data-limited or rapidly changing environments. This framework facilitates seamless integration across clinical, veterinary, and ecological domains.

Overall Integrative Perspective

Taken together, these technological domains converge to establish a unified AI-enabled healthcare ecosystem capable of predicting risks before disease emerges, providing personalized and precise treatment, integrating human–animal–environmental health, and strengthening diagnostics, therapeutics, monitoring, and biosurveillance. This integrated perspective supports broader goals in global health security and promotes the development of sustainable health systems across disciplines.

CONCLUSION

Altogether, this review serves both as a perspective on present innovations and as a prospective guide to how AI, ML, and bioengineering will continue to transform One Health and global health security. The power of AI and ML mentioned in the articles here has enabled advances in health information. It is recognized that groundbreaking advances in genomics, biomarker research, pharmacogenomics, nanotechnology, and bioengineering are transforming the face of traditional medicine and dentistry. AI applications, including medical imaging analysis, pathology detection, radiotherapy optimization, and digital health, have accelerated disease diagnosis and treatment. AI in virtual health, wearables, and remote patient monitoring is further making healthcare more accessible and patient-friendly.

At the heart of this change is the mounting acceptance that human, animal, and ecological well-being are profoundly interconnected. Initiatives of One Health have come together to organize interdisciplinary collaborations that address global health challenges, their future, and what is at stake.

Altogether, it is imperative to recognize that the future of AI in health informatics lies in the development of meta-AI frameworks empowered by MCP. This is a novel agent-based system that orchestrates multiple AI tools for context-aware, adaptive decision-making, enhancing clinical performance even in data-scarce, evolving healthcare environments.

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CONFLICT OF INTEREST

The authors declare no conflict of interest.

CONTRIBUTIONS OF INDIVIDUAL AUTHORS

GAC, ZS, and FA conceptualized the study; TE and GAC designed the tables and figures; GAC, ZS, FA, and TE wrote and enhanced the manuscript.

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