RESEARCH PAPER

A Global Bibliometric Analysis on Harnessing Digital Transformation in Pharmaceutical Industry

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ABSTRACT

The pharmaceutical industry is changing based on digital technologies, with artificial intelligence (AI), blockchain, big data analytics, the Internet of Things (IoT), and telemedicine integrated to become more efficient, innovative, and provide better care to patients. The review was based on a bibliometric and narrative method according to PRISMA and included any literature published since 2000 in major databases, such as PubMed, Scopus, and Web of Science. They were visualized as thematic clusters, citation impact, and research trends with the help of VOSviewer, SciVal, and R-based network centrality analyses. Findings showed that digital health publications grew exponentially with three leading clusters that were AI-driven drug discovery, blockchain-based data traceability, and remote healthcare through telemedicine-enabled healthcare. This analysis has indicated the growing interdependence of clinical research, digital innovation and regulatory frameworks. Other challenges to the widespread adoption of blockchain technologies include data interoperability, privacy, scalability, and adaptation to regulations. It is discussed that global policies need to be unified, AI implementation must be ethical, and digital tools should be accessible to everyone. To sum up, the digital transformation is reformulating the science of pharmacology by joining technology to health provision, pushing the development of Pharma 4.0, a digital future in which predictive, personalized, and sustainable digital ecosystems will support the innovation and equity of health in the world.

Keywords: AI, IoT, VOSviewer, SciVal & R-based network.

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Introduction

The digital transformation has been redefining the healthcare sector by incorporating the use of modern technologies and applications like artificial intelligence (AI), the Internet of Things (IoT), big data analytics, and cloud computing. According to the European Parliament and Council, this transformation was to integrate the use of digital technologies to modernize the delivery of business and services [1]. Within healthcare, this change has been dubbed as healthcare 4.0 because the changes are expected to increase precision medicine, enhance patient outcomes, and automate healthcare processes with advances such as Electronic Health Records (EHRs), telemedicine, and patient wearables [2]. The privacy, integrity and data security can be enhanced using technology like block chain and federated learning, which enables real-time sharing of data, speedy diagnosis, and monitoring of patients remotely [3].

Digitalization is not without serious challenges such as data interoperability, cybersecurity and regulatory compliance [4]. According to the definition provided by the World Health Organization (WHO), digital health can be described as the use of digital technologies in health-related activities, which range in the innovations that enhance healthcare access, efficiency, and quality. This kind of digital transformation is becoming all the more crucial to solve the world problems such as ageing, labour shortages, and the escalating cases of chronic illnesses [5].

Similarly to the healthcare sector, the pharmaceutical industry is also experiencing the same digital transformation. The recent Industry 4.0 and Industry 5.0 paradigms focus on automation, sustainability, and patient-centricity, which is similar to healthcare digitalization. AI and robotics, coupled with data analytics, improve the customized medicine, speed up research and development, and manage supply chains. Contract Development and Manufacturing Organizations (CDMOs) will have to make sure that such digital efforts are aligned with Good Manufacturing Practices (GMP) and have strict collaboration between the stakeholders [6].

This study will set out to investigate the radical purpose of digital technologies in defining the future of the pharmaceutical industry. The study aims to assess the optimisation of drug discovery, clinical trials, personalised medicine and supply chain management through these innovations as well as deal with the regulatory hurdles and interoperability [7]. It also seeks to focus a bibliometric analysis of literature, key theme, as well as trends in the field. The main goal addresses how digital technologies can be used in transforming the pharmaceutical industry in the future with the aim of maximizing drug discovery, clinical trials, personalized medicine and supply chain management. The study highlights the huge potential of these technologies in transforming the pharmaceutical operations, enhancing health outcomes across various regions globally, and advancing the growth in the future [8].

Materials and Methodology

According to the PRISMA-S guidelines (supplemental figure 1 & supplemental table 2), the methodological rigor and transparency of this narrative review are ensured. All eligible studies were independently screened and assessed by the authors (GS and SP). In cases of disagreement, consensus was reached through discussion [9], [10].

Strategies for Searching:

A thorough search of the literature in PubMed was performed to determine peer-reviewed articles published between January 2000 and March 2024. The Boolean operators were incorporated in a comprehensive search strategy that is presented in Supplementary table 1). The searches were limited to English-language and full-text articles. The search strategy was narrowed down to studies about the digital transformation, artificial intelligence, blockchain, telemedicine, electronic health records, and other technological advances in the pharmaceutical sector. The search was broadened with the use of Boolean operators (AND) and truncation symbols (so that the results would be relevant to the search). PublMed was searched with controlled vocabulary (MeSH terms Medical Subject Headings) and other databases corresponding keywords were modified [11].

Data Analysis:

The combination of bibliometric and network-based analytical methods was used to analyze the data. VOSviewer (version 1.6.7) was used to create co-occurrence network maps and images of clusters of keywords, collaboration of authors, and citation patterns. This facilitated the determination of the new areas of research and interconnecting topics in the digital transformation scenario of the pharmaceutical industry. The tools that were used to assess the institutional and author productivity, citation impact, and global research trends were SciVal analytics, which offered quantitative data on the scientific performance. Moreover, centrality metrics such as degree, betweenness and closeness centrality were determined using the "igraph" and bibliometrix R packages to measure the influence and connectivity of important terms and authors within the bibliographic network [12]. The pattern of research was easily interpreted descriptively and inferentially with these integrated tools, identifying high-impact areas, collaborative networks, and changing directions of digital innovation in the pharmaceutical field [13].

Results

Descriptive statistics:

The obtained articles amounted to 19904 articles that were screened against duplication leaving a total of 19203 articles that were included in the study as indicated in supplementary figure 1. The studies of digital transformation in the pharmaceutical sector between the years 2015-2024 reveal an annual growth of 1,383 academic contributions of 9,226 authors working in 548 cross-national collaborations as illustrated in Figure 1. The total number of citations is 88,722, at a mean citation of 64.2 per publication, which is high (supplementary figure3). The total Field-

Weighted Citation Impact (FWCI) was 3.37, more than three times the global average, and the median FWCI (1.46) demonstrated generally good results in most of the publications. Interestingly, 34.6 percent of outputs were in the top 10 percentile of field-weighted citation percentile, with the field having a high-impact research presence (Supplementary Figure 4). The United States, China, the United Kingdom, India and Saudi Arabia were the top contributors, and Harvard University as well as the University of California, San Diego were the top institutional contributors (Supplementary Table 3). The largest portion of output was represented by prominent sources of publication, e.g. Sensors, Healthcare (Switzerland), and Scientific Reports, which were multidisciplinary (Supplementary table 4). Altogether, the bibliometric measures indicate the active development of the sector fields toward the digital innovation, international cooperation, and translational influence, which strengthens the tendency to consider digital technologies as the increasing center of the practice in the field of pharmaceutical science and industry.

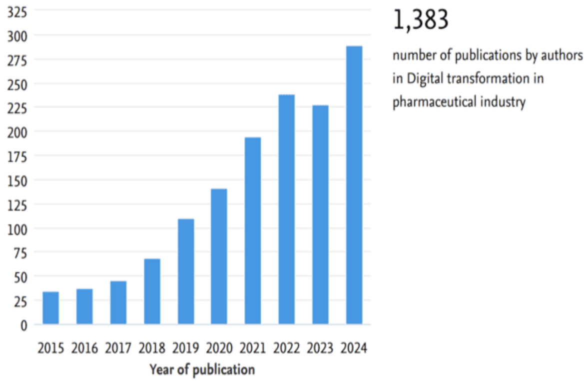

Figure 1: Publication trend and scholarly output

Core Digital Technologies and their Applications:

Historical evolution:

The development of the modern pharmaceutical science and technology started at the end of the 19th century and continued up to the World War II. Such important disciplines as pharmacology, bacteriology, and biochemistry appeared in Europe. Japanese modernized under the Meiji Government, with medical regulations and western medicine replacing the traditional one. Science and engineering thrived in modern education around the world, and in Japan, 29 schools of pharmacy were built, some of which were later closed. The role of pharmacists was also not much since the doctor was permitted to prepare medicines. The pharmaceutical industry in Japan expanded after World War I, and the companies that were formerly wholesale merchants would change to pharmaceutical manufacturers. There was an advance in research of the problem of public health such as beriberi, but little role was played by the pharmacists. Important pharmaceutical breakthroughs were made including the cure of syphilis by Ehrlich-Hata and the identification of adrenaline by Takamine. During World War II, chemotherapeutics, antibiotics and research on vitamin improved all over in Japan, England, and America [14]. Pharmaceutical science and technology in Japan have a history of 50 years since World War II which can be divided into nine major stages. To begin with, the Japanese pharmaceutical sector was reconstructed in 1945 under U.S. influence with the emphasis being placed on the production of penicillin and the introduction of new scientific fields such as biochemistry and microbiology. Between 1951 and 1960s, Japan was importing several new drugs and technologies in the U.S. and Europe, rapidly modernizing its pharmaceutical industry, but it initially used imitation. The 1956 to 1970s were the years of sudden growth of the Japanese companies due to the active vitamin K analogues and OTC medications, which meant that research laboratories could be extended. There was the concern in the 1970s that led to public concern of drug safety especially because of the SMON disease, which led to a shift to the development of ethical drugs. New laws on pharmaceuticals were also introduced during this period so as to have the efficacy and safety of the drugs. In 1976, the Pharmaceutical industry in Japan started to concentrate on original research as opposed to imitation. Since 1985, there has been innovation in drug effectiveness testing, diagnostic methods, medicine analysis, and computer aided drug design. There were various major new drugs that were discovered within the period 1970 and 1995, which included cephalosporins, quinolones and calcium antagonists. Lastly, the dramatic trend of internationalization of the pharmaceutical market in 1990s resulted in attempts of harmonizing regulatory practices with international levels, with the Japan Pharmaceutical Manufacturers Association defining future approaches in a 1990 report [15].

The industrial revolution has passed through four major phases. The process of the shift of agriculture to mechanized industrialization started in the 18th century and culminated in Industry 1.0, as a result of the invention of the steam engine and railroads. The late 19th to early 20th century saw industry 2.0, which brought in mass production where electricity was used and assembly lines, thus changing the manufacturing process. In the late 20th century, industry 3.0 introduced digitalization and automation and used electronics, computers, and robotics to streamline manufacturing and business processes. In the 21 st century Industry 4.0 brings together cyber-physical, IoT, big data, and AI to build smart, connected, and efficient manufacturing spaces, improving sustainability and operational efficiency via highly innovative technologies [16]. There have been four stages of development of health care between Health Care 1.0 and Health Care 4.0. Health Care 1.0 comprised elementary patient-clinician contacts in the diagnosis and treatment. As science is advancing in terms of medical equipment, Health Care 2.0 brought forth new medical technology such as MRIs and surgical robots that can be used to improve diagnosis and treatment. The emergence of electronic health records (EHR), digitalization, and telehealth became a part of Health Care 3.0, changing the clinical process and making the recovery possible at a distance. Health Care 4.0 is a system comprised of IoT, AI, cloud computing, and big data integrated into a smart system. The priorities of this revolution are proactive care, disease prevention, personalized medicine, and more active participation of patients and caregivers in disease monitoring and decision-making.

Electronic Health Records (EHRs):

Patients' demographics, medical history, diagnoses, medications, lab tests and imaging are all stored in one digital warehouse in electronic health records (EHRs) [17]. HRs have gone to become part of the healthcare system, having been used by more than 80% of the hospitals in the United States and Canada since their development in the sixties and adoption by governments in the seventies as part of the national healthcare system. Increased functionalities System of data exchange, clinical decision support, and computerized physician order entry all have increased the quality, safety, and efficacy of care. Figure 2 derived bibliometric network showed that EHRs, personalized medicine, and clinical trial optimization are highly linked as they have become more interdisciplinary. The effect of EHR-integrated alert systems on medication safety is also featured in studies- they indicate that 96% of the recommendations were accepted and the instances of adverse drug event, metformin overdose, and paracetamol dosing errors were severely reduced [18]. The implementation of EHRs has disrupted clinical decision-making and patient-centered care as a whole.

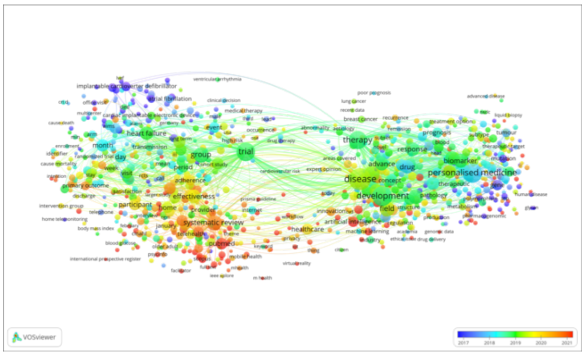

Figure 2: Co-occurrence network visualisation of EHRs

Telemedicine

The technology of telemedicine dates back to the 1950s when an image could be transmitted between the hospitals and this has developed into an important part of the modern healthcare system as it supports remote consultations, management of chronic illnesses and the provision of tele pharmacy services [19]. This increase in the availability of the internet, smartphone, and 5G networks has increased its target to include eICUs, telesurgery, and real-time monitoring, making access to these services much more accessible to rural and underserved groups [20]. Figure 3 (Bibliometric mapping) indicates the increasing relation that telemedicine has with personalized medicine, clinical trials, and adherence monitoring, suggesting that it has become an element of pharmaceutical service. It has proven itself in clinical practice, wearable ECG sensors enhanced cardiac follow-ups [21], and telephonic follow-ups were equal to face-to-face meetings in epilepsy management at reduced costs [22]. Nonetheless, there are still issues, such as technical limitations in monitoring chronic diseases and socio-demographic differences in using telehealth, especially in minority populations. The newest innovations, including mobile ultrasound with 5G capabilities, allow improving the accuracy of diagnostics and the rate of data transfer in preclinical and emergency scenarios even more [23]. Table 1 underscores the different studies that use telemedicine that have been incorporated in the study.

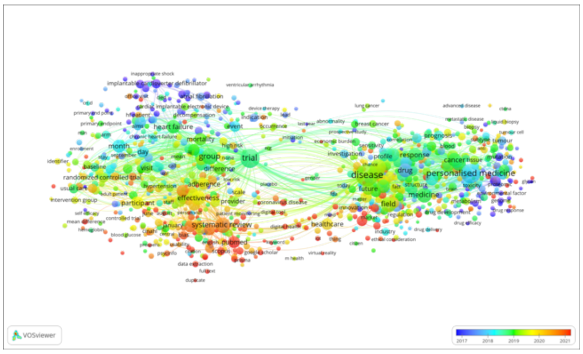

Figure 1 : Co-occurrence network visualisation of telemedicine keywords

Table 1 : Telemedicine utilisation

Study/Project	Focus	Key Findings	Challenges/ Notes
Bhavnani et al. [24]	Wearable ECG monitors and mobile apps in telecardiology	Enabled continuous monitoring for cardiac patients, reducing hospital visits	Facilitated real-time monitoring and remote medication adjustments
Epilepsy Telephonic vs. Face-to-Face (FC) Consultations	Telephonic vs. face-to-face consultations for epilepsy patients	No significant difference in breakthrough seizures; Telephonic consultations averaged 10 minutes (vs. 22 minutes FC) and were INR 865 cheaper	Telephonic reviews improved patient satisfaction and access, with fewer lost to follow-up
Gaveikaite V et al. [25]	Telemedicine for chronic conditions (e.g., diabetes)	Telecardiology made strides, but tools for chronic conditions like diabetes are lacking	Technical barriers in tracking disease-specific indicators for chronic conditions
Chunampet Rural Diabetes Preventive Project	Telemedicine for diabetes management	Enabled timely follow-ups and medication adjustments, improving glycemic control	Showcased telemedicine's role in better diabetes management
NYU Langone Health Study [26]	Racial disparities in telemedicine utilization during COVID-19	Black patients increased telemedicine use but were less likely than white patients to use telemedicine (aOR 0.60); more likely to test positive for COVID-19 after telemedicine visits	Highlights racial disparities in access and outcomes, need for targeted interventions
Telehealth for Liver Care During COVID-19 [27]	Disparities in telehealth utilization based on socio-demographic factors	Gaps in telehealth access by age, race/ethnicity, insurance, and marital status; lower completion rates for Hispanic, Black, and Medicaid patients	Video consultations offer better assessments but face technology access and comfort issues
Berlet et al. [28]	5G-enabled preclinical diagnosti	Successful 5G data transmission with average	Emphasized the importance of core slicing to

	cs using mobile ultrasound	round-trip latency of 10 ms; high-quality image/video streaming	optimize data transmission for telemedicine

Mobile Health(mHealth)

Mobile health (mHealth) is a concept outlined by WHO as the application of mobile and wireless technologies in healthcare, but nowadays it is expanded to cover various technological, clinical and behavioural areas. Figure 4 (Bibliometric mapping) showed that the key words of mHealth related to medication adherence, remote monitoring, and clinical trials formed strong clusters, indicating that mHealth has become an important aspect in managing cardiovascular and chronic diseases. The studies show that mHealth has been used to enhance medication compliance in many countries using SMS messaging, mobile apps and interactive voice response mechanisms. These interventions increased adherence as well as improved blood pressure and cardiovascular outcomes. The additional reported sustained changes of systolic and diastolic blood pressure decrease after mHealth interventions. More comprehensive efforts, including the mWellcare, and programs, by India, have been using mobile technologies to better access to medication, maternal education, and chronic disease management, particularly in underserved populations. Table 2 summarises different researches that outline the medication adherence strategies that make use of mHealth.

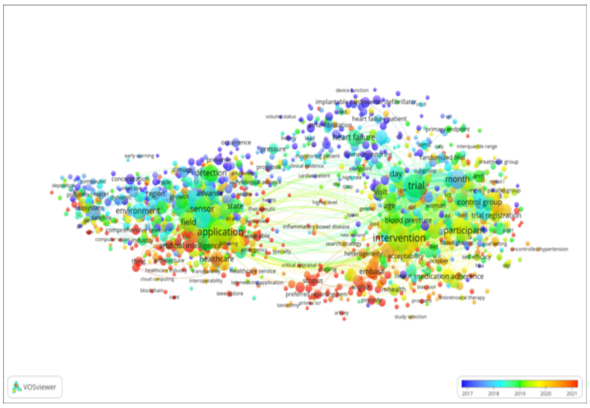

Figure 4: Co-occurrence network visualisation of mHealth

Table 3: Studies utilising mHealth in medication adherence

Study	Location	Sample Size	Duration	Intervention	Adherence Measurement	Outcome
France Study	France	5546	1 month	SMS-based intervention	Arachidonic acid-induced platelet aggregation	Improved medication adherence; no significant impact on blood pressure; cost-effectiveness noted
USA Trial (90 participants)	USA	90	1 month	SMS reminders + SEAMS	MMAS-8	Significant improvement in medication adherence
USA Trial (21,750 participants)	USA	21, 750	12 months	Interactive voice interventions	Modified PDC	Significant improvement in adherence for cardiovascular and diabetes management

Malaysian Study	Malaysia	62	2 months	SMS reminders	MMAS-8	Significant improvement in adherence for ischemic heart disease
Chinese Trial (280 participants)	China	280	6 months	SMS + Micro Letter (ML)	MMAS-8	Improved adherence, particularly in coronary heart disease patients
South African Study	South Africa	1372	12 months	Interactive text messages	PDC	Improved adherence to hypertension medications; significant decrease in blood pressure
USA Study (179 participants)	USA	179	12 months	Web-based app with reminder alarms	Not specified	Significant improvement in adherence to CVD medications; reduced missed doses
USA Trial (413 participants)	USA	413	6 months	Wireless pill bottles with automated messages	Not specified	Significant improvement in adherence
Chinese Study (445 participants)	China	445	3 months	SMS reminders	MMAS-8	Improved adherence and blood pressure reduction in hypertensive patients
Ni Z et al. Study	China (Rural)	Not specified	Not specified	mHealth intervention	Not specified	Improved adherence, reduced SBP and DBP, no significant impact on

						heart rate
Prabhakaran et al. "mWellcare"	India	Not specified	Not specified	Telemedicine	Not specified	Improved medication adherence for hypertension and diabetes
Kilkari Program (Maternal Education)	India	Not specified	Not specified	Digital reminders + telemedicine	Not specified	Improved access to medications and health services for women and children in rural areas
m-MITRA Project (Infant Care)	India	Not specified	Not specified	Telemedicine	Not specified	Improved access to medications and health care services for rural populations

Artificial Intelligence

There are a number of AI models used in healthcare, which are highlighted in Table 3. Autoencoders (AEs) are mostly applied to unsupervised learning, the task of which is dimensionality reduction and reconstruction of the original input. Some of the AI technologies have become part of the healthcare industry, such as machine learning, natural language processing, as well as expert systems useful in diagnostics, clinical decision support, and drug discovery. Figure 5 (refer to bibliometric mapping) showed that two major clusters are the role of AI in precision medicine through an analysis of electronic health record (EHR) and the use of AI in drug design and molecular optimization. State-of-the-art algorithms, such as Autoencoders (AEs), Adversarial Autoencoders (AAEs), Variational Autoencoders (VAEs), and Generative Adversarial Networks (GANs), can be used to generate molecules and design de novo drugs. Molecular sequence prediction is further improved by recurrent Neural Networks (RNNs) and the Long Short-Term Memory (LSTM) architectures. It was demonstrated in studies, such as Schultz et al., that VAEs were successful in creating NMDAR antagonists, whereas ORGAN and ORGANIC frameworks improved inverse-design chemistry. Drug repurposing has also experienced advancement through deep learning and graph neural networks (GNNs) that utilize genomic and EHR data to uncover other therapeutic targets, especially opioid use disorder [29].

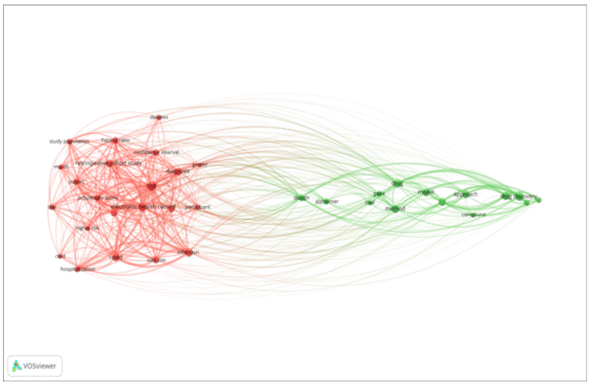

Figure 5: Co-occurrence network visualisation of AI in drug discovery and precision

Table 4: Top AI models used in Healthcare

Method/Model	Application	Description	Challenges/Notes
Autoencoders (AEs)	Dimensionality reduction, reconstruction, molecular representation, de novo drug design	Compress molecular data into latent spaces, useful for chemical space exploration and reconstruction	Focused on unsupervised learning for molecular exploration

Adversarial Autoencoders (AAEs)	Oncology research, generating new anticancer compounds	Combines AEs with GANs to improve generative capabilities	Improved generative abilities for molecular design
Variational Autoencoders (VAEs)	Drug design, novel drug compound generation (e.g., NMDA receptor antagonists)	Probabilistic autoencoders that transform input data into latent distributions, capable of generating new molecular structures	Flexible and widely used for molecular exploration, generating novel therapeutics
Generative Adversarial Networks (GANs)	Drug discovery, chemical structure generation	Consists of generator and discriminator models, used to generate realistic molecular data	Challenges in molecule validity
Recurrent Neural Networks (RNNs)	Drug design, molecular sequence handling (e.g., SMILES strings)	Processes sequential data, often enhanced with LSTM or Gated Recurrent Units (GRU)	Vanishing gradients; fine-tuned with reinforcement learning or transfer learning
Long Short-Term Memory (LSTM)	Handling sequential data, drug design	Addresses challenges of RNNs (e.g., vanishing gradients), suitable for molecular sequence prediction	Enhances RNN performance for molecular sequence design
Graph Neural Networks (GNNs)	Drug-target identification, modeling biological systems	Models complex relationships in biological data, useful for drug discovery and target identification	Emerging as powerful tools for biological data analysis
Machine Learning (ML)	Drug repurposing (logistic regression, SVM)	Traditional models applied to drug chemical structures, gene expression, and protein interactions	Basic approaches compared to deep learning methods
Deep Learning (DL)	Drug repurposing (DNN, CNN, LSTM)	Enables automatic feature extraction from high-dimensional	Enhanced drug repurposing prediction accuracy

		biological data	
Mendelian Randomization (MR)	Drug repurposing, causal relationship analysis using pQTLs and gene expression	Analyzes causal relationships in drug repurposing	Useful for integrating genetic data into drug discovery
ORGAN/ORGANIC	Inverse-design chemistry, drug-like molecule generation	GAN architectures for generating molecules with specific target properties	Molecule validity remains a challenge

Block-chain technology

Decentralized and tamper resistant ledger system known as blockchain technology is being used more and more in healthcare to achieve secure and transparent and patient centric data management. Correcting the current situation by storing the electronic health records (EHRs) in the form of Non-Fungible Tokens (NFTs), the patients can retain ownership of their records, access, and guarantee data traceability and privacy. Blockchain and NFTs can be used in pharmaceutical supply chains to improve their level of product traceability, counterfeiting, and authenticity throughout the distribution channels. The new models such as Ethereum, Hyperledger Fabric and Quorum can be used to achieve smart contracts that automate consent management and clinical trial processes and guarantee compliance and privacy. Decentralized storage systems like IPFS are useful in improving scalability and security of large medical datasets. ERC-20 (incentives) and ERC-721 (medical records) are token standards that enable transparent exchange of data using rewards. In general, blockchain promotes the democratization of data, improves the interoperability, and boosts trust, which is a paradigm shift in the safe digital healthcare ecosystems. This network visualization in figure 6, based on the keywords "blockchain in healthcare" and "supply chain," highlights key connections between terms central to both fields [30].

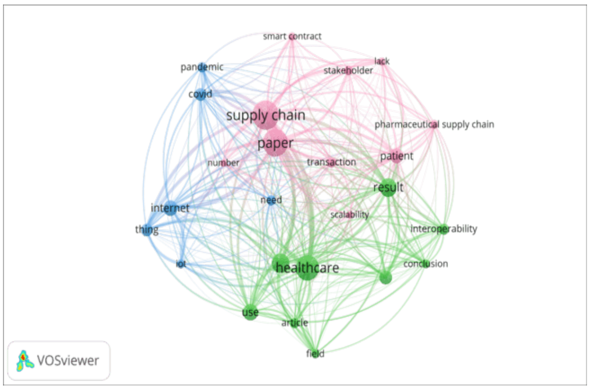

Figure 6: Co-occurrence network visualisation of blockchain technology in health care

Digitalization in business models

Digitalization has transformed the pharmaceutical business by enhancing quality control, regulatory adherence and traceability of supply chain using serialization and cloud-based integration. The visualization of bibliometry (Figure 7) shows that digital technologies, artificial intelligence (AI), and healthcare business models are becoming increasingly more converged, with cost optimization and better patient outcomes being the main areas of focus. Research findings indicate that digital transformation improves the sustainability and traceability of pharmaceutical supply chains. One study has shown that traceability plays a major role in the positive outcome of digital transformation on sustainable supply performance, which confirms the effectiveness of blockchain and IoT in providing safety and conformity. The suggested an upgraded model of a digital system with issues in demand forecasting, logistics, and risk management, which will encourage a self-reflective supply chain to enhance collaboration, efficiency, and resilience. In aggregate, these results suggest that the incorporation of digital technologies led to operational excellence, sustainability, and competitiveness, and contributes to the development of smart, responsive, and transparent pharmaceutical systems.

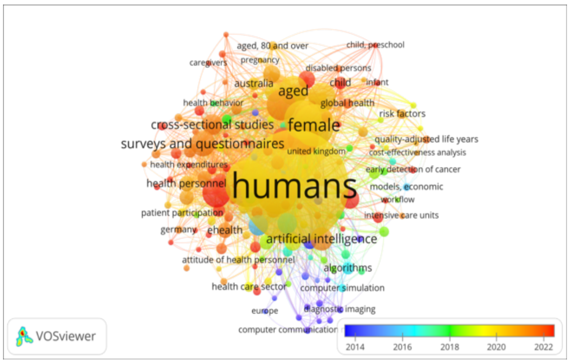

Figure 7: Co-occurrence network visualisation of digitalisation in health care and pharmaceutical business models

Bibliometric Analysis

The centrality evaluation of the top 100 keywords together (Figure 8) formed in the digital transformation of the pharmaceutical industry shows that the word "humans" has the highest degree of centrality and eigenvector centrality (1.0000), which dominates the research network. The degree centralities of keywords like female and male are also high (98 and 98) along with the closeness scores (0.4304 and 0.4108) showing the significance of the keywords in gender-oriented biomedical research. The most apparent (degree = 95; eigenvector = 0.8565) is "animals" which means its high frequency of co-occurrence in preclinical researches. Such technical and methodological terms as reproducibility of results and algorithms are evidence of high network integration, which is associated with the growing concern with the issue of research validity and with computational modelling. Specifically, the drug design and solubility fall in the middle betweenness and closeness centrality of the two fields of research, and as such, they play connective roles in the research interdisciplinary field. As shown by the visualization, there exists a high density of interlinkages between clusters of biological models, AI technologies, and pharmaceutical chemistry. In general, the centrality scores of the human-centered and computational terms are high, which is an indicator of a developing ecosystem where artificial intelligence, drug development, and clinical trials are combined to produce more translational and reproducible results in the age of the digital era. Table 4 presents the top 10 keywords with centrality metric and full evaluation of top 100 keywords is presented as as an appendix table 5.

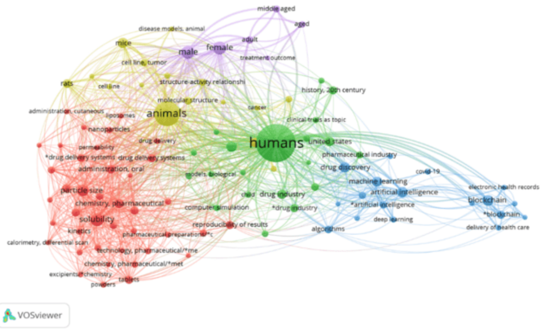

Figure 8: Network visualisation of top 100 combine key words in digital transformation in pharmaceutical industry

Table 5: Top 10 Keywords by Centrality Measures in the Keyword Co-occurrence Network

Rank	Keyword	Degree	Betweenness	Closeness	Eigenvector
1	humans	99	0.0000	0.0784	1.0000
2	female	98	0.0056	0.4304	0.3687
3	male	98	0.0025	0.4108	0.3870
4	animals	95	0.0003	0.3438	0.8565
5	reproducibility of results	95	0.0014	0.3929	0.0768
6	drug design	91	0.0068	0.4541	0.1498
7	time factors	90	0.0214	0.5156	0.0512
8	solubility	89	0.0004	0.4323	0.1900
9	drug design	88	0.0007	0.4160	0.1874
10	algorithms	88	0.0013	0.4231	0.0844

Discussion

The late 19 th century and the post-World War II periods were the time of significant changes in the pharmaceutical industry, as Europe led the way to pharmacology, bacteriology, and biochemistry, and Japan shifted to the period of imitation to innovation by 1970s. Since then, the emergence of Industry 4.0 and Health Care 4.0 has brought a new digital paradigm that is based on AI, IoT, and big data. The bibliometric network studies showed that the digital transformation is integrated in terms of innovation, research-driven by data, and ethical governance through three main groups, namely, drug discovery and biotechnology, clinical trials and risk assessment, and regulatory oversight. EHRs, telemedicine, and AI have transformed personalized medicine and optimisation of trials, but continue to face challenges in harmonisation of regulations and application in the real-world. Recent studies identify automated alert systems, tele pharmacy, and mHealth as digital innovations that enhance safety and adherence but have some shortcomings such as alert fatigue, data fragmentation, and socio-demographic differences. Equally, blockchain and NFTs contribute to increased patient data control and traceability of a supply chain, yet the scalability and interoperability are a hindrance. GANs, RNNs, and VAEs are AI and deep learning models that have revolutionized drug discovery, but problems with interpretation and prediction prevent clinical translation. Rising complexity of trials and the necessity of inclusive and data-driven trial populations is highlighted in the 2021 Tufts Report as multimorbidity expands worldwide. Even though a lot has been achieved, there exist loopholes in the adoption of technologies within healthcare systems. The next generation of research needs to concentrate on equal access, interoperability, ethical governance, and personalized digital strategies to realize sustainable and patient-centered pharmaceutical innovation.

Limitation and future prospects:

Although the adoption of digital technologies in the pharmaceutical industry has been particularly fast, there are a number of obstacles preventing the implementation of such technology in large scale. Issues of data security, privacy, scalability, and interoperability continue to be a concern, despite the application of blockchain and NFTs. The industry is lagging in terms of digitization compared to other sectors such as the finance or aerospace sector with manual processes still prevailing in the clinical trials. The compliance with the Good Manufacturing Practices (GMP) is often the regulatory barrier that delays the approach to AI-driven innovation. Moreover, AI-based models like GANs and RNNs also lack interpretability and validation, which restrict clinical trust. There is also the limitation to equal access to telemedicine and mHealth technologies by socio-economic and racial factors.

Moving forward, predictive analytics, AI-based drug discovery, and personalized medicine will be designed to focus on future trends with an optimized result using big data. Blockchain will improve the data visibility and drug traceability, whereas telemedicine, wearables and smart applications 5G-enabled will broaden the scope of remote care. The production will be transformed by Pharma 4.0 innovations like smart automation and 3D printing of customized medications. With the advancement of these technologies, it is necessary to have a keen eye on cybersecurity, interoperability, and dynamic regulatory rules to facilitate safe, fair, and scalable application of these technologies across the healthcare systems in the world.

Conclusion

The pharmaceutical landscape is undergoing digital transformation, which defines a new world of technological innovation and patient-centered healthcare. As pointed out in this review, the combination of artificial intelligence (AI), big data analytics, blockchain, Internet of Things (IoT), telemedicine, and mHealth has already started to transform each drug development and delivery process, i.e., the process of discovery to post-marketing surveillance. The technologies boost efficiency, openness, and customization at the same time minimizing expenditure and human error. Nevertheless, their potential is limited by regulatory intricacy, data compatibility, cybersecurity threats, and unfair access. To be implemented successfully, digital transformation should go farther than pilots' adoption to apply to the entire system, with good governance frameworks, proven algorithms, and responsible data utilization. Pharma 4.0 is in the future of intelligent automation, real-time analytics, and adaptive clinical trial designs which are informed by digital twins and predictive modeling. The solutions based on blockchain have the potential to transform confidence and traceability throughout the international supply chains, and 5G and wearable-enabled telehealth have the ability to bring precision care to distant populations. The only way to make the most of these advances is working together between industry, regulators and academia to create single digital standards and to offer inclusivity in accessing technology. Finally, sustainable digitalization in the pharmaceutical industry will not only speed up the innovation process, but also democratize healthcare and allow shifting to reactive to predictive and preventive medicine, where not only therapies are developed more rapidly, but also smarter, safer, and affordable to everyone.

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