DIGITAL TRANSFORMATION IN THE BIOLOGICAL SCIENCES: A COMPREHENSIVE PERSPECTIVE FROM THE DISCIPLINE OF BIOSCIENCES WITHIN THE FUTURE PROFESSORS PROGRAMME

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ABSTRACT

The concept of digital transformation (DT) has revolutionized different facets of society including institutions of learning, where it has continued to influence teaching, learning and research. Over time and with the continued technological advancements in biological science disciplines, it has become clear that the increased convergence between these disciplines and digital systems application will become more apparent. For example, the advent and application of next-generation sequencing (NGS), machine learning (ML), artificial intelligence (AI) and other automated biological processes have afforded unique huge data sets with high societal impact. As such, digitalization of the bioeconomy remains necessary. The digitalization of the biosciences has birthed emerging concepts like “digital biology”, “engineered biology” and “bio-revolution” and involve computer-centered biosciences. These are built around the integration of scientific data, modeling at several levels, as well as networked science. Nonetheless, it is still plagued by information derivation policies and technicality issues. Although, digital biology has seen a major boost in recent years with the emergence of new and updated digital biology databases and platforms for advanced computational modelling, and connection and visualization of bio-data at a molecular level, more efforts are needed from governmental stakeholders (policy makers), industry and academia to enhance the impact of computational automation and digital transformation in bioscience activities. Hence, a steady upscale in digitalization of the biosciences would ensure bioprocess development, increase teaching, research efficiency and productivity, birth more innovative future applications for various industries, and thereby impact several aspects of life. This article presents how selected biological science disciplines have been digitally transformed through data analytics and how the concept could be further explored in advancing teaching, learning and research.

Keywords: Digital transformation, Biological sciences, digitalization, higher education, automation, process development

INTRODUCTION

In the advent of increased computational power and cheaper computers, digital innovations have become more accessible. Still, compared to engineering industries, the bioscience sector has shown slower uptake and adoption of digital transformation (DT) technologies, especially with respect to the efficient simplification and modernization of bioprocesses for product and service development. The engineering industry has since embraced digitalized 2D and 3D predictive and screening models to mimic, measure, and compare desired and actual research outcomes, enhancing overall output from the field. However, in the biological sciences, the pressure for workflow digitalization was made more apparent by the COVID-19 pandemic, as the life sciences and biopharmaceutical industries had to step up to mitigate infections spread within a short space of time. The pandemic further showed that it was possible to accelerate product development and reduce regulatory bottlenecks in the approval process for biopharma products (Chaudry and Uvhagen 2023). The COVID-19 scourge also revealed the urgency for higher educational institutions (HEIs) to transition from conventional research, teaching and learning (RTL) methods to a more wholistic and digitalized educational system (Mospan 2023; Thanachawengsakul and Thanyavinichakul 2020). It has also become evident that to survive in the evolving digital space, the bioscience RTL sectors must shift from traditional methods to higher throughput technologies and big data-driven platforms. The Claptek industry report of 2020 showed that over 80 per cent of life science and biopharma organizations agree that DT could provide new growth opportunities. Industry based DT professionals have also suggested that across all RTL institutions, abiding by DT norms is key to attaining value-centric product/service delivery, as opposed to an economy based solely on revenue generation (Claptek 2020).

The concept of DT alongside the emergence of novel technologies provides several biobased opportunities in varied industries (pharmaceutical, agricultural, life sciences research), and affects supply chains, manufacturing protocols, how finance is optimized and research conduct and regulation. In the biological, life or natural science fields and subfields, digitalization or DT has become a key strategy in advancing the capacity of these sciences to make better, holistic impact on RTL outcomes. The digitalization of the bioscience fields may be viewed as a mitigator of risk, and an enabler of both existing and emerging new biological sciences technologies. Despite the ability of new digitalized technologies to boost institutions' competitive edge for continued future relevance, digitally transformed workflows in HEIs or RTL institutions still have the propensity to disrupt conventional protocols when met with great resistance. As such, the presence of non-rigid institutional cultures and progressive leadership are key to DT (Dolata and Werle 2007; Dohrmann 2023).

The biological sciences sector is a largely regulated industry that has steadily increased in complexity, and experiences fast-paced technological advancements such as evolution of novel digitalized medical care products. Likewise, there is an increase in end-user interaction with digitalized bioscience-based products and services such that health data tracking, generation, monitoring, storage, and sharing may require tighter data management policies. Although many bioscience disciplines are open to the opportunity to explore DTs, compliance levels to ensure a sustained and consistent DT adoption vary widely. For example, too few biopharma-based research citadels (about 20%) have fully embraced digitalization (Dohrmann 2023). These digitally mature institutions also adopt stage-wise implementation, starting with small to pilot scale, to measured DT initiatives with each stage based on lessons learnt and developed from prior stages and initiatives. Unfortunately, most institutions are more comfortable with a slow-paced or no adoption of digitalization. In the grand scheme of things, an overall approach is needed to harness the potential deliverables of DT. Digitalization adoption strategies should be built on the need to optimize new and emerging cloud, blockchain, data analytics, machine learning (ML), artificial/cognitive intelligence, virtual or digital reality technologies in data gathering and scaling across the institution. This DT background would then facilitate a sustainable culture of RTL, supportive leadership, and collaboration (Bresnahan and Malerba 1999; Dolata 2008).

A typical institutional DT framework should cover efficient execution and engagement, as well as catalyze new bioprocesses and products for value addition (Mhlanga, Denhere, and Moloi 2022). The successful delivery of these key strategy levels remains a daunting task. Nevertheless, its effective uptake and implementation could be facilitated when each strategic level is subdivided into mini activities and projects that contribute to the targeted whole. The upgrade of the bioscience industry to one with a digital footprint and fingerprint could help to align future innovative outlooks of relevant industry stakeholders and partnerships. While digitalization has its pros, the cons of DT should also not be undermined (Zolkover et al. 2022; Barry 2024).

Embracing DT in the biological sciences to favourably impact on RTL outcomes could mean a refinement or overhaul of current conventional approaches and raises certain risk concerns like the level of reliability/trustworthiness of emerging and evolving DTs to ensure data, product, and process safety, and required regulatory compliance standards. Nonetheless, rather than constitute a barrier to DT, these drawbacks may be circumvented with the realization that risk cannot be totally eliminated in any process but should be backed by workable transformative steps to address them as against delaying the opportunities tied to digitalization

(Dohrmann 2023). Again, while no one-size-fits-all approach exists to DT, the creation of a digital footprint and outlook that enlightens the paths to novel and creative means and opportunities should remain the key DT goal (Hall and Soskice 2001; Malerba 2004). An "openness to change" would be the watch phrase for the successful adaptation to the current wave of DT, and this article gives an appraisal of this concept.

TRENDS AND BUZZWORDS IN DIGITALLY TRANSFORMED BIOSCIENCES

Operations within the bioscience sector experience enhanced profitability and efficiency due to novel data lakes, cloud computing and Artificial Intelligence (AI)-based tools. Although in their early stages of development, digital twinning, and quantum technologies are under exploration by many institutions. DT provides agile and scalable applications for major improvements in data gathering, processing and discovery speed, and secure data and information collation, sharing, and storage, irrespective of distance and location (Gkrimpizi, Peristeras, and Magnisalis 2023; KMS Healthcare 2023). New platforms have also paved the way for innovative ways to monitor drug impact, bioprinting, and formation of smart bioscience hubs which contribute to advance the concept of individualized healthcare, as well as optimize drug discovery and development drives (Patrinos and Mitropoulou 2022).

As an overarching term which stems from the computer science sector, AI targets the production of machines that are intelligent enough to touch many aspects of RTL and also simulate them, take up language, formulate concepts, and solve problems for humans while improving and evolving themselves (Turing 1950; National Science Foundation US Report 1995). Terms like ML, deep learning (DL), and AI are related, but each of them still possess distinctive attributes. While AI is a much broader field of intelligence, ML is its subdiscipline used for digital computer training and can deliver on tasks in the absence of specific rubrics via the utilization of data insights and trends. On the other hand, deep learning as a ML offshoot based on artificial neural networks (ARNs) is multilayered to facilitate decision making and learning, and used in projects requiring large data set analysis. Examples include ChatGPT and DALL-E2 (Holzinger, Kickmeier-Rust, and Müller 2019). AI may be symbolic (knowledge presented in form of symbols) or generative (smarter, more end-user interactive and adaptive) (Bratko and Muggleton 1995; Muggleton et al. 2018). The use of AI-based platforms thus has the capacity to enhance recognition of patterns, assessment and capturing of data in the varied bioscience fields and applications (Joshi 2021).

AI-based biotechnology innovations have also been reported to contribute to the rapid attainment of global sustainability development goals (SDGs); wellbeing and health, delivery of portable water and energy, food security, climate change action, promote sustainable use of terrestrial and under water ecosystems and forest management, fight desertification, and biodiversity conservation. Trending subjects in AI/ML-biotech applications include biomedical ontologies, network pharmacology (Akoonjee et al. 2022), knowledge-based reasoning, spatial and temporal inferencing and representation, uncertainty reasoning and decision support, data mining, big data analytics, areas covering explainable AI methods (XAI), and natural language processing (NLP), with biotechnological applications (Holzinger et al. 2023).

Furthermore, DT in biosciences, decentralized blockchains, and healthcare trees have enhanced drug dosing and help to ensure patient medical history protection while receiving tailored and optimized care (KMS Healthcare 2023). Again, with increased automation, trends can be analysed to predict future demands and occurrences. The application of digital twin technologies also aids the remarkable creation of virtual replicas of actual structures, processes, and instruments. Virtual replicas are used by bioscience experts to simulate infection conditions at a higher level, culminating in improved rapid results, and long-term reduction of therapy expenses (KMS Healthcare 2023). The digital ecosphere therefore has a holistic approach to wet-lab, preclinical, diagnostic, and therapeutic predictions, with a focus on precision diagnosis for early detection of disorders and treatment.

In basic principles, data is the key input and driver of DT and innovations. Data facilitates the exploration of new research fields, and avenues for service and product development. It also provides insights on emerging market supply and demand spaces and how production could be optimized to meet demands. Digitalization fuels innovations like the internet of things (IoT) and 3D printing and fast-tracks innovative workflows. Digital innovations also speed up testing, product design and prototyping, and in such way that incorporates swift feedback from end-users. Also, most innovations are derivatives of strong collaboration where overall costs, benefits and reduced risks are shared. These advancements in the biosciences ecosystem create new emphasis for governmental policies that encourage and ensure DT benefits (Organization for Economic Co-operation and Development OECD 2019).

The pushback from the biosciences against DT could be attributed to inadequate talent/capacity, capital, and issues surrounding operating models which cover 57 per cent, 58 per cent and 52 per cent, respectively, in most cases (KMS Healthcare 2023). So, successful digitalization of the sector requires some form of digital maturity check. Digital maturity checks imply measuring and comparing the advantages and disadvantages of conventional and digitally transformed techniques and processes prior to making an informed choice to adopt digital trends. This is followed by measuring value metrics (expected versus actual benefit), and creating DT innovation portfolios to sync goals across the bioscience value system. This requires an exhaustive fit versus gap assessment to determine which existing technologies and capabilities could meet the goals and which new investments are necessary. Then, in determining the actual approach to take, respective bioscience fields may choose to partner, acquire, or build in-house digitalized solutions that are flexible enough to stand the test of time and align with defined goals (KMS Healthcare 2023).

DEVELOPING CAPACITY IN EMERGING DIGITALIZED BIOSCIENCE TECHNOLOGIES

Digitalization has facilitated the emergence of novel bioscience platforms. Likewise, the evolution of existing and new consolidated databases by growing communities of researchers contribute greatly to big data processing, analyses and management, as well as the derivation of new insights into the molecular levels of life. Some of the new platforms fall within the fields of computational and systems biology, and bioinformatics. Functional biosensor and biomarker-based imaging, DNA based transient and transformation expression and nanotechnology tools have also emerged. These generate huge amounts of complex “big data” that require a multidisciplinary approach to research and development (R&D) programs. However, in syncing technologies across the various fields the challenge of language barriers must be circumvented. This is where continued training and capacity development become important (Dolata 2008; NSF US Report 2023). Another means of bridging the language gap is by modifying or updating teaching and learning (T&L) processes to become more multidisciplinary. Capacity development in emerging biosciences platforms may also be enhanced by the conservative use of resources, sharing of high-value and high-throughput infrastructural and human resources, and encouraging inter-lab and inter-agency collaboration. In the same vein, academic and industry directors and policies have key functions in advancing human capacity development (HCD). Administrators should encourage the breaking of respective field limits or boundaries to foster cross-disciplinarity and collaboration among scientists, faculties, and industry stakeholder. Likewise, institutional (government, industry, academia) adaptations and collaborations are key to promoting interdisciplinarity and circumventing R&D infrastructural bottlenecks (Streeck and Thelen 2005; NSF US Report 2023).

DIGITALIZATION IN KEY INTERLINKED BIOSCIENCE NICHES – BIOTECHNOLOGY AND BIOLOGY

Biotechnology – A union of biology, technology, and engineering

This is a fast-paced interdisciplinary bioscience field encompassing the exploration and application of living systems (as a whole or part, their pathways, and products) to enhance industrial processes and proffer solutions to technologically relevant challenges. Biotechnological questions are also mostly tackled at the molecular strata. As a core niche, it networks with mathematics, applied science, microbiology, biochemistry, chemistry, engineering, biomedical and biophysics sub-fields, among others. This encompassing biotechnology field possesses an immense capacity to foster process and product-based innovations as key gains from varied societal sectors, and without undermining the contributions of other sub-specializations. The medical, marine, and agriculture industries make up the major beneficiaries of technological advancements in this core niche. The contribution of DNA-based techniques can also not be overemphasized in the birthing of biotechnology-based products (Paratela 2023).

As a fast-paced niche, scientists in the science, technology, engineering, and mathematics (STEM) fields have been in a race to derive lasting and innovative products or processes (Penprase 2018), in the light of climate change and multidrug resistance challenges that have long-term deleterious effects on developed and developing world economies. Since the field continuously evolves, scientists have had to keep abreast of the latest technological developments in the field and learn, re-learn and upgrade skills to remain relevant. The application of genetic engineering methods has fostered novel intellectual properties (IPs) and patents from research institutions around the world. A huge potential exists in this multidisciplinary field for innovation-based collaborations focused on techniques and platforms for comprehending infections' mechanisms, creation of novel therapeutic interventions, and studying bioprocesses (Paratela 2023). Another emerging and largely accepted trend in the fourth industrial revolution (4IR) of the biosciences is the increase in remote/offsite RTL, in view of increased adoption and digitalization of educational processes. This forms the bases for the emergence of "microcredentials" or degrees and certifications earned from online education (Young 2017).

Additionally, the synergy of biotechnological processes with AI-centric systems have also been key to driving successes in the exploration of deep waters as bioscience researchers can now avail themselves of the use of virtual reality (VR) and robotics in off-site operations. Explorers who investigate the deep seas have recorded new forms of microscopic life in otherwise uncharted territories. AI has also impacted biotechnology in the facets of edited foods and creation of novel proteins (Joshi 2021). Other AI-biotech applications include environmental monitoring, predictive modelling, resources, inventory, pests, and infections management in forestry (Nothdurft et al. 2021; Holzinger et al. 2022), and agricultural biotechnology (Zhu et al. 2016). Also, AI/ML is useful in drug and image screening, novel drug targets identification, and predictive computational modelling, as related to medical or biopharma biotechnology (Holzinger et al. 2022), computomics and bioinformatics (Trivedi et al. 2020). Still, optimal gains from AI/ML-based techniques are stalled by algorithms that are unable to back trace outcomes or infer solutions from outputs to human experts (Müller et al. 2022). Despite this critical concern, rapidly growing AI-biotech based applications would continue to have long-term influence on the biotech sector.

Interestingly, the biotechnology-based processes and many more have since embraced the concept of digitalization to better manage and understand the enormous data sets that have been generated over time in the field. These DTs further enhance potential bioactive products or drugs screening, novel products and process design, discovery, and development (Aribisala et al. 2022; Oloche et al. 2023), and thus pave the way for industry, health, agriculture and environmental sustainability-based solutions for a sustainable future on planet earth. Biotechnological processes digitalization has contributed greatly to fast-track breakthroughs in commercialization and R&D drives, especially as data sets emanating from various industries are more rapidly and efficiently curated and processed using cutting-edge technologies to deliver new treatment strategies and precision healthcare (Patrinos and Mitropoulou 2022), for example, AI in cancer care (Xu et al. 2019). Despite the drawbacks of DT including issues surrounding data derivation, validation, pre-processing, and storage protocols, insufficient enabling policies, data integration, cyber or "cloud" security concerns, the societal benefits remain significant and cannot be overemphasized. Enacting enabling digitalization policies, alongside the embrace of varied data sets, consolidated databases, industry-wide collaborations, and emerging novel technologies are key to biosciences digitalization reaching its full potential (Gkrimpizi et al. 2023; Paratela 2023).

Biology – looking out for all higher life forms

The study of "life" in relation to living systems on varied strata comprises a complex molecular mix of intriguing machineries. The milieu of highly regulated "life" machineries consists of nucleic acids, membranes, proteins, intra- and extracellular metabolites which form the bases of intricate interactions and networks in cells. These biological factors are also subject to exogenous stimuli such that inherently complex dynamics ensue over time. At all levels of complexity, from the smallest to the higher forms of life, cellular, tissue, organismal and ecosystem interactions occur, and are studied using contemporary and novel approaches that give improved and new scientific insights (Instituto de Tecnologia Química e Biológica 2023).

The emergence of modern, novel, and high throughput biological techniques generates large data sets. The building of predictive models for enhanced decision making with little or no human intervention have also been facilitated by novel technologies. As such, in the past decade, this research discipline has experienced digitalization at the molecular (genome) level, particularly in the areas of data annotation and assembly, new pharmaceuticals and biosynthetic strategy development, efficient derivation of data analytics algorithms, and design of synthetic organisms and biomolecules. This DT trend would maintain a continued upward trend with the provision of enhanced and unparalleled computer-based algorithms, models, and high-powered processing clusters to effectively navigate artificial intelligence (AI), robotics, ML, and the evolution of big data concepts. Beyond the emergence of high throughput machines, now more than ever, computational and systems biologists (integral DT actors) who comprehend the interconnectivity languages between life and *in silico* (computational) analytical technologies are needed. This could ensure a readiness to tackle future challenges like disease outbreaks that could occur. The DTs in biology are unstoppable and biologists must evolve in order not to get lost in the tidal digitalization trend (Instituto de Tecnologia Química e Biológica 2023).

Digitalized R&D workflows have the capacity to transform the biological sciences space. However, success is dependent on effective collaboration among professionals to develop improved visions of digitally transformed work environments. Biotech-based small, medium, and emerging institutions are capital intensive ventures, with an average R&D expense per medication output reaching over $950 million from 2009 to 2018 (Wouters, McKee, and Luyten 2020). It takes about eight or nine years to get a Food and Drug Administration (FDA) approved drug to the target population or patients due to regulatory hurdles governing clinical investigations prior to approval (Agrawal, Ahlawat, and Dewhurst 2021). Fortunately, drug trial to approval time is being accelerated due to DT factors that fast-track the usually arduous drug approval processes in the face of emerging global infections (COVID-19), intensified competition, and increased industry complexity (Wong et al. 2022).

Emerging technologies surrounding digitalized biology, biohacking or synthetic biology generate significant quantities of data and information compared to old-fashioned research methods. In addition, researchers continue to gain concurrent insights into the workings of living systems and underlying pathways associated with various bioprocesses and diseases leading to rapid scientific discoveries like novel antibodies and vaccines. Another example is the mainstreamed emergence of “Meta AI” and “AlphaFold” which enhance the ability to solve protein folding problems while opening up new explorable research ideas and opportunities in the pharmaceutical industry and synthetic biology. The biology niche has also produced digitalized solutions from next-generation sequencing (NGS) and other platforms. To efficiently manage, analyze, interpret, and visualize NGS big data, *in silico* approaches have been useful in raw sequence data processing and analysis (pre-processing, file conversion, filtering, reads alignment to genomic reference, variant calling), varied statistical, network and pathway analyses, and structural and functional annotations. In addition, models which are subscribed to, for example, CellxGENE for RNA sequence data analyses and access, have also been launched by industry actors to empower gene/cell therapy developers and experimental biologists in bioinformatic systems handling and development (eLabNext 2023). Again, in areas of dosage management, personalized nutrition or medicine, image processing and analysis, genetic engineering (gene editing), drug discovery, and radiography, AI is also being effectively used. Hence, the future could further benefit from precision diagnostics and the delivery of more inexpensive healthcare due use of AI-centered technologies. The techniques are also channeled into agricultural waste reduction to maximize farm output and reduce farm to market delivery time (Dutta, Nikhil, and Girish 2022). Besides, the use of smart AI/ML and DL application programs have facilitated the modification of living systems' metabolic pathways by increasing the number of premium outputs from little or few input. Examples may be seen with the use of enhanced microbial strains in bio-based industrial processes to enhance or optimize product yield (Bhardwaj, Shristi, and Dhananjay 2022).

In terms of T&L, biology instructors are required now, more than ever, to update their method of delivery in such a way that is digitally transformed via the use of digitalized T&L resources. Studies have also shown that the use of digitized T&L materials significantly enhanced the overall ability of students to participate, learn and develop themselves in the biological sciences. Likewise, DTs in biosciences T&L also increased the rate at which students gain and apply new project-relevant skills (Sumatokhin et al. 2020; Bassey 2001). Nonetheless, some bioscience instructors and students still found it difficult to apply and navigate the assortment of digitalized T&L resources available to them (Sumatokhin et al. 2020). Hence, digitalizing RTL, individual student and educator, and bioscience subject environments should be the norm to enhance adaption and acquisition of digital skills, as well as RTL outcomes (Hyypiä et al. 2019; Langeloo et al. 2019).

CHALLENGES, GAINS AND WAYS FORWARD IN DIGITALIZATION OF THE BIOSCIENCES

In the past decade, the biological (life) science fields have seen a rapid technological shift in data upsurge from high throughput workflows. Besides the huge data generation, data interpretation, teaching and understanding of new digitalized workflows constitute herculean tasks that require continued training and re-learning. As such, RTLs and other bioscience-based institutions are under immense pressure to rapidly blend in with transformative upskilling trends (Cheema et al. 2022). In addition, other challenges to DT of RTL experiences in HEIs such as difficulty with estimating return on digital investment (Alenezi 2021), poor coordination across Departments (Marshall 2018), constrained budgets, inconstant or imposed governmental polies for HEIs, data security and infrastructure concerns, inadequate digitalized support services, unwelcoming attitudes and belief systems, dearth of holistic vision, strategic plans and leadership, resistance to change, among others, may be circumvented within the space of highly adaptive institutional frameworks (Gkrimpizi et al. 2023; Mhlanga et al. 2022). To increase the probability of attaining DT of current workflows, transparency, and an increased willingness to adopt relevant digitalization strategies are integral. All actors driving DT initiatives including relevant resource persons or consultants are uniquely positioned to deliver much needed training, and education to improve development and learning (D&L) outcomes. The benefitting organizational RTL teams gain new and updated knowledge on innovative DT regulations, the nature of evolving digital ecosystems, and product/service end-user education (Dooley 2021). Digitalization also has the capability to facilitate the derivation of smart and translational bioscience-based contributions to the global SDGs for enhanced global health and wellness, and environmental ("green", climate-smart applications) protection (George, Merrill, and Schillebeeckx 2021; Mondejar et al. 2021).

Furthermore, since the advent of the world wide web, robotics, IoT, ML, and AI that power data-driven predictions and findings in real time, and the emergence of more miniaturized products, there has been a surge in digitized information available from bioscience-based product/service users. This points to an added responsibility on life science institutions to educate students, workers, patients, and other forms of end-users on the best ways to navigate emanating data and information from varied sources, so that challenges like the lack of digital literacy and adequate infrastructure could be better overcome (Aditya, Ferdiana, and Kusumawardani 2022; Gkrimpizi et al. 2023). This could be achieved through active institutional bioscience D&L teams. Digitalization has brought data closer to end-users, making them a key part in the process of decision-making. User-friendly digitalized tools and platforms are also useful in empowering data end-users and transfer of updated knowledge. Following proper execution, education drives have also proved valuable in facilitating end-user satisfaction and increased investment in life science deliverables (Dooley 2021). Also, compliance to DT regulations is nonelective, even though non-compliance remains a key bioscience industry concern. The inability to comply with regulations is worsened by the confusion and tediousness of training programs. So, institutions need to design DT workshops to be more target role-based, hands-on, relevant, and engaging for optimal end user experience (UX). Compliance processes may also be digitalized to enhance the data analytics and reporting processes (Parker 2020; Alzahrani et al. 2021; Dooley 2021).

These trends emphasize the need to invest in biosciences DT, though capital-intensive. Experts in DT have reported that while analyzing responses from actors within the bioscience fields, only 15 per cent of institutions agreed that full compliance and adoption of DT-based projects were key in achieving institutional goals. Over 25 per cent were reportedly confused by the DT investments and process which partly reflected the urgency for DT implementation created by COVID-19 emergence (Bayram et al. 2020). Since then, DT education and training in bioscience RTL teams have contributed greatly to expatiating on DT "hows" and "whys", and the enhancement of stakeholders' investment in life science fields (Dooley 2021). Additional DT gains include the reduced gap between scientist, doctor, and patient (patient tracking, virtual clinics), an empowered (quantum computing, data analytics) genomic sector for tailored personalized healthcare, and improved research pace for delivery of products (wearables and drugs), and T&L services (Campbell 2022; Patrinos and Mitropoulou 2022). Also, while it is essential to increase bioscience-based discoveries and outputs, and practice effective data management and communication in DT, stakeholders (researchers, funders, beneficiaries) should associate enhanced laboratory-based procedures to return on investments in order to achieve DT in research facilities (Black 2022).

Factors such as prevailing institutional strategies, services and products, existing protocols, personnel capacity, the amount of data generated and the presence of relevant technologies, have been identified as integral determinants of DT adoption in the life science fields. Of these, the most important determinant factor for HEIs was the data generated. As such, the more data-driven a process the more likely it is to drive digitalization needed to oversee data gathering, processing, access, storage, analysis, and backup (Tungpantong, Nilsook, and Wannapiroon 2022). The type of DT approaches to be adopted depend on the aim, value outlook and scope of the transformation and not merely on digitalized technologies themselves (Kane et al. 2015). The sustainability of a transformed system is linked to several approaches (Verhoef et al., 2021) which may take the form of high throughput digital assets establishment; the institutional structure (for example, learning partnerships, technology-centered workflows, experiential RTL, teacher and learner centric activities, targeted goals and metrics, and strategies for advancement (diversified, adaptable curricula, and data-driven platforms for open access sharing) (Lachman and Wojciech 2022).

DT OF BIOSCIENCES RTL IN SOUTH AFRICA – LOGICAL INFERENCES FROM FPP

In synergizing the preceding discussions directly relevant to South African HEIs, we must now note that the South African Department of Higher Education and Training (DHET) had intensified efforts to ensure heightened interdepartmental collaborations and equal access to national infrastructure platforms to transform RTL outcomes and HCD [for example, the implementation of the University Capacity Development Programme (UCDP)]. These efforts were in a bid to assure the emergence of "merited" professorial status of future emerging or established scientists and academics from its HEIs (Bitzer 2008). Additional laudable programs targeting all-round capacity building (leadership, management, RTL, DT, etc.) of future professors include the University Staff Doctoral Programme (USDP), New Generation of Academics Programme (nGAP), Nurturing Emerging Scholars Programme (NESP), Existing Academics Capacity Enhancement Programme (EACEP), Higher Education Leadership and Management (HELMP), the current Future Professors Programme (FPP) (Breetzke and Hedding 2018).

As a DHET initiative centered around collaboration among over 25 HEIs and RTL partners, the FPP aims to build a new crop of professors from the milieu of senior lectures, lecturers and equivalent academic staff, and boost their capabilities for greater impact in their RTL fields (in this case, the biosciences). It encourages the building of new research collaborations, interdisciplinarity, inter-department, peer and institution networks to boost the capacity of "future professors" for excellence and transformative impact across several disciplines by providing feasible solutions to societal challenges (Thompson 2023). The program covers the assessment of promising fellows' current community service and RTL skills, and identification of improvement areas that are filled using mentors, coaches and advisors. Engagements at related trainings, seminars, workshops also incorporate detailed discussions on the roles of the professoriate and emerging topics in academia such as DT needs and benefits to the biosciences. In fostering its systematic vision, it promotes intellectualism, and international networks for broader knowledge interchange (Thompson 2023; Corporate Communication and Marketing Division Stellenbosch University 2021).

Since inception of its phased cohorts in 2021, it has strengthened HEI systems, diversity, inclusivity, innovation and networks. The programme is also highly adaptive. For instance, COVID-19 hastened the need for DT of RTL experiences and showed the vulnerability of fellows in HEIs. Academics workload increased, same as the demand for quick adaptation to new, digitalized learning management systems (LMSs) to ensure continued RTL. For fellows, the FPP was restructured to include counsellor and coach interactions to reduce the sense of isolation and better cope with difficulties linked to changes occurring at their HEIs (Corporate Communication and Marketing Division Stellenbosch University 2021). Furthermore, institutional adaptions to the pandemic varied depending on the presence or absence of adaptive frameworks before the pandemic. Depending on available infrastructures, South African HEIs were able to maintain forms of remote function (as seen in the Collaborative Online International Learning (COIL) context], while the gradual return to physical, on-site delivery of services resumed as the pandemic eased out (DHET 2020; Mhlanga et al. 2022). In light of the foregoing, the ability of the FPP to adapt and evolve to current and future challenges depicts its ability to effectively shape the educational landscape of the biosciences for continued national and global relevance for decades to come. The FPP awakened in us a new level of educational service delivery awareness, and the need to unlearn, learn and re-learn new practices and skills in the face of ongoing DTs, while remaining scholar-centered and fluid in an unrestrained, productive and healthy work space.

CONCLUSION

Over the next few years and distant future, DT in biosciences will evolve and requires continuous RTL capacity building across all actors and stakeholder organizations. Such HCD via digitally transformed initiatives ultimately targets the enhancement of operational workflows and commercialization potential of bioscience industry outputs. Likewise, DT programs aimed at changing negative perceptions, increasing awareness, knowledge and comprehension levels of the life science industry complexity, and its associated end users, and employees, are continuously needed. The use of appropriately suited technologies and DT consultants by bioscience institution-based D&L teams are key to fast-tracking DT processes engagement, as well as its holistic adoption and implementation in the biological sciences.

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