



The Future of Data Storage: A Comparative Analysis of DNA Technology and HDD

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Abstract: The global data storage demand is predicted to grow. The costs of maintaining and transferring data, also demand advanced solutions. Despite substantial advancements in the field of DNA data storage technologies, commercial activity remains undeveloped. In this research the commercialization prospects of DNA storage technology are discussed. Through a comprehensive review of fundamental research, the most recent advances in DNA data storage technology in comparison to the leading hard disk drive data storage sector are revealed. The analysis encompasses companies developing the technology. The research shows that both scholarly and patenting activities within this domain are escalating, mirroring the evolutionary trends observed in existing commercialised technologies. Alternatively, there is an increasing magnetism for this technology in the data industry, with US dominance substantially outpacing the EU in terms of successful commercialisation initiatives. The exploration of a transdisciplinary bridge between industry, academia, and government attests to the critical influence of this collaboration for the streamlining of commercialisation process. Therefore, the research emphasises the profound impact of targeted state funding in bolstering commercialisation efforts. For DNA data storage technology to transition from a scientific possibility to a commercial reality, strategic enhancements in transdisciplinary cooperation, supportive regulatory frameworks, and dedicated funding are paramount.

Keywords: DNA data storage; commercialisation; innovation; triple helix.

1. Introduction

With modern advocacy for digitalisation [1] and digitalisation as a solution for sustainable and effective advancement in data management and storage [2], increasing digital data generation is predicted to reach 175 zettabytes by 2025. This will experience a 229% rise compared to the year 2021 (79 zettabytes). Technological advancement enhanced humanity moving from physical data storage to a digital form of storage, i.e. from simpler visible memory storage like floppy disks and CDs to more complicated hard drives and cloud storage. Every step later with every innovation the size of physical hardware has been decreasing and the density of information stored in the same space has increased. Currently, data storage relies on magnetic, optical, solid-state, and cloud-based technologies, allowing music, sounds, pictures, words, and movies to be stored in a binary form.

However, current data storage technologies are reaching both their technological and resource availability limits [3]. Expanding data centre areas offers only a short-term solution. This approach has a damaging environmental impact due to high energy requirements. Additionally, it is financially demanding, as current data storage technologies need replacement every 10-20 years [4]. Researchers, such as Mendell [5] advocate that digitalisation is a harmful phenomenon and suggest reducing data generation by slowing down the process itself. Nevertheless, there is a long-term technological solution that will enable data storage in much larger quantities than current capabilities allow, the 1953 discovery of the double helix gave rise to contemporary molecular biology, focusing mostly on understanding how genes regulate the chemical processes within cells [6]. The discovery yielded ground-breaking insights into the genetic code [7] and protein synthesis [8] that were crucial to the development of new and potent scientific techniques, including recombinant deoxyribonucleic acid (DNA) research [9], genetic engineering [10], rapid gene sequencing [11], and monoclonal antibodies [12], the techniques on which the current multibillion-dollar biotechnology industry is based [13]. Significant scientific developments, such as genetic fingerprinting

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and contemporary forensics [14], the mapping of the human genome [15], and ongoing gene therapy research [16], have become essential parts of the modern innovations market. And the fundamental function of DNA for storing immense amounts of data densely and compactly has not been exploited yet.

There has been a significant increase in research on commercially viable DNA data storage technology arguing the potential of future disruptiveness [4], [17-20] during the last twenty years. It was escorted by rapid patenting of technology-related findings and discoveries that could benefit further commercialisation and scalability of the technology [21], new cooperations between tech and biotech giants are being observed, resulting in the creation of new environments for transdisciplinary efforts between different industries, institutions, and societies, as well as emphasising industries' interest in further development of the technology. Furthermore, with increasing geopolitical instabilities and the fragility of supply chains even governments have shown interest in alternative storage solutions. Despite the mentioned governmental acknowledgment, there has been an observably significant difference between the popularity of the technology within the US and EU considering the financial and social involvement. As well as the number of existing and newly created companies dedicated to the technology's development.

There is a significant advancement in the understanding of the fundamental principles of the field of DNA digital data storage technologies, however, there has been comparatively little commercial activity in this field. This research aims to evaluate the prospects for commercialising DNA storage technology. It seeks to understand why existing efforts have not yet yielded a commercially viable product and explores ways to accelerate this process. As well as how far scientific research together with patenting of intellectual property has developed compared to already existing hard disk drive (HDD) data storage technology. It provides insights into whether the accumulated scientific knowledge suffices or if further development paths exist. This is followed by an analysis of commercialisation efforts within the EU and US by comparing the number of existing and newly created companies that are involved in developing DNA data storage technology and further investigation of transdisciplinary cooperation role and necessity for successful commercialisation of the technology.

2. Materials and Methods

Research has been conducted by triangulating literature review, statistical analysis and developed authors' insights to provide more accurate and detailed conclusions and recommendations. To analyse and evaluate the prospects for DNA data storage commercialisation, we conducted a statistical analysis of three main variables: scholarly activity, patenting activity, and commercial involvement. This approach is similar to Katherine E. Dunn [22] research on origami technology. Supplementing this research with additional insights into commercialisation activities within the US and EU, as well as, exploring potential transdisciplinary cooperation models within existing commercialisation effort. Katherine E. Dunn [22] has conducted analysis of patent applications and research activities as well as company case studies of DNA nanotechnologies, however, excluded DNA data storage technology from the sample.

In this research same approach of analysis has been chosen to analyse commercialisation efforts and additionally, a referent variable has been added. Referent variables have allowed to compare DNA data storage tendencies with already well-established technology tendencies. As a referent variable HDD technology has been chosen as it is currently used as a technology for archival data storage, as well as it is already broadly commercialised. Moreover, for the research "Lense" scholarly and patenting database has been chosen as it connects 422 million datasets of publications from "Microsoft Academic", "CrossRef", "PubMed", "And core", "OpenAlex" as well as, patenting datasets from major patenting offices. "Lense" database allows to application of extensive queries and filters to extract only relevant entries. All entries have been filtered for the timeframe of the last twenty years from 2000 to 2021 (Appendix A, Appendix B), taking a decade for the initial time frame. In such cases, DNA data storage-specific queries for scholarly activity and patenting activity have been created as part of the research to extract only valid scholarly and patenting activities related to DNA data storage. Using the same approach, a query, for scholarly activity and patenting activity of HDD storage has been created and extracted (Appendix C, Appendix D).

For commercial activity analysis, companies have been selected by analysing publicly available sources, such as webpages, LinkedIn profiles of the companies, annual reports, pages of official associations dedicated to DNA data storage technology development, research papers and articles. Additionally, using the Lens database, companies were identified based on the patents submitted and research papers published. Search of the companies has been segmented according to findings of literature review: *industry* (biotechnological (Biotech) industry, technological (Tech) industry); *region of operation* (United States (US), European Union (EU)); *Contribution towards development and commercialisation of DNA data storage technology* (Companies or start-ups that

are actively and directly developing DNA data storage technology, Companies or start-ups that are actively developing components or processes of DNA data storage technology and claim that their development can be used for DNA data storage: in the biotech sector (including enzymatic DNA synthesis, in vivo and in vitro data storage, improved DNA storage media, particle stabilization, and nanostructure) and tech sector (encompassing AI, decoding and encoding algorithms, and hardware/software development) and Companies or start-ups that are members of alliances and associations that are claiming to be a part of DNA data storage technologies but not directly involved in development).

Furthermore, data from Organisation for Economic Co-operation and Development (OECD) has been gathered regarding governmental funding in the science, technology and innovation sector, which includes OECD Research and Development Statistics (RDS), Eurostat, Statistics on Research and Development, UNESCO Institute for Statistics (UIS) data. All gathered data has been structured using Microsoft Excel, and statistical analysis and visualisations have been created using GraphPad Prism software.

An understanding of scholarly activity and patenting activity is necessary to determine the connection between these two variables as well as their connection and influence on commercial activity. Furthermore, a referential variable has been included to forge insight into where each variable of developing DNA data storage technology stands alone compared to already commercially active HDD technologies variables. For the statistical analysis linear regression and Spearman's correlation analysis have been conducted. For linear regression analysis significance value (P) and goodness of fit value (R²) have been extracted and analysed.

Scholarly activity and patenting activity between the EU and the US have been analysed and supported by the additional variables of governmental expenditure in the science, technology and innovation sector to evaluate the correlation between governmental impact on scholarly activity and patenting activity. The comparison analysis has been supported by linear regression analysis. Furthermore, the commercial activity variable has been expressed by the amount of commercially active companies related to DNA data storage. Commercial activity has been compared between the US and the EU. Upon developing a database of companies, it has been noticed that not all companies are equal contributors to commercialisation of DNA data storage, however, the involvement of each of them is of equal importance. Therefore, the company involvement scale has been developed by the authors to evaluate the distribution of companies between the involvement levels:

1. Biotech or tech companies or start-ups that are actively and directly developing DNA data storage technology;
2. Biotech or tech companies or start-ups that are actively developing components or processes parts of DNA data storage technology and claims that their development can be used for DNA data storage;
3. Biotech or tech companies or start-ups that are members of alliances and associations that are claiming to be a part of DNA data storage technologies but not directly involved in development, as well as, owning a patent related to DNA data storage technology or are involved in funding of DNA data storage technology.

3. Results

3.1. Comparative analysis of DNA data storage and HDD technologies scholarly activity

One of the major challenges for DNA data storage technology is the passage of the valley of death that bridges the research part with the commercial part of the process. From the literature analysis the authors have established that DNA data storage still has some technological development ahead to successfully enter the market and serve as an attractive solution for archival data storage. Therefore, the success of research activities becomes an integral part of the commercialisation process. By analysing the general pattern of research activities, we can establish the potential interest that DNA data storage technology is generating among the research community. Figure 1 demonstrates that comparing well-established technologies like HDD scholarly activity with still-developing technologies of DNA data storage scholarly activity the total amount of publications released between 2000 and 2021 is significantly different. HDD-related scholarly activity is 2.55-fold higher than DNA data storage technology. However, the difference could be explained by the fact that HDD technology has been in commercial use since 1952 and research efforts have been catalysed by commercial companies both in funding and internal research as product development efforts.

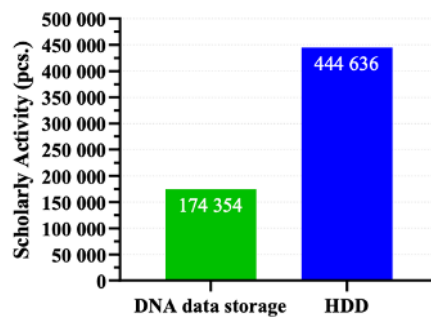


Figure 1. The total scholarly activity of DNA data storage and HDD technology between 2000 and 2021.

The general trend of DNA data storage technologies scholarly activities has been upwardly increasing ($P < 0.0001$; $R^2 = 0.957$) (figure 2a). Comparing years 2000 and 2021 research activity has increased by 3.29-fold. Indicating research communities' acknowledgment of the major potential that DNA data storage technology can bring to the market. Furthermore, increasing research activity indicates, that funding for DNA data storage research is also increasing. Figure 2b shows upwardly trending research activity of referential technologies, however, the confidence in further increase is lower than DNA data storage technologies ($P = 0.0001$; $R^2 = 0.5365$). The existing similarity between the two technologies can indicate that DNA data technology has the potential to be commercialised.

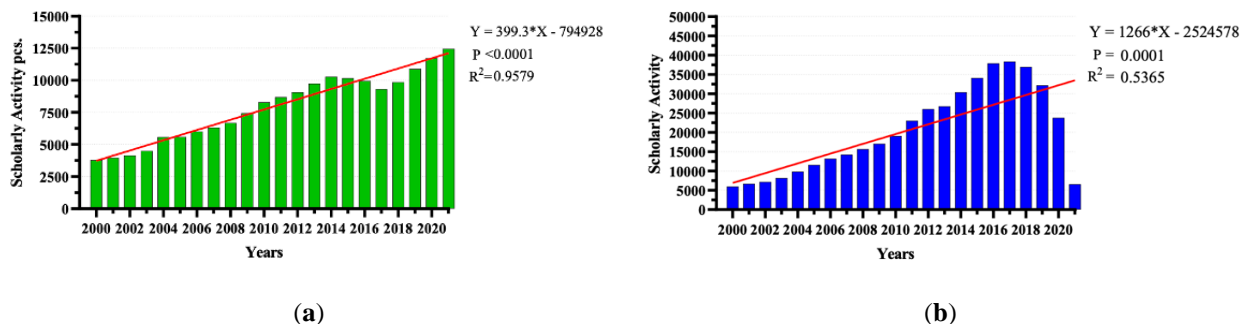


Figure 2. (a) Scholarly activity of DNA data storage technology from 2000 to 2021. (b) Scholarly activity of HDD technology from 2000 to 2021.

While comparing DNA data storage scholarly activity with HDD scholarly activity it was noticed that while DNA data storage research had a minor decrease in scholarly activity during period of 2014 – 2017, starting from 2017 it started rapidly increasing and exceeding previous years (Figure 2a). However, HDD scholarly activity has begun decreasing since 2017 (Figure 2b) and almost reaching the activity of the year 2000 (2000=5994, 2021= 6567). Therefore, Spearman's correlation was performed to understand if there is a connection between the increasing DNA data storage scholarly activity and the decreasing HDD scholarly activity. Spearman's correlation (Figure 3) showed that there is a strong negative correlation ($r = -0.9524$, $p = 0.0011$) between DNA data storage scholarly activity and HDD scholarly activity. Indicating, that increasing DNA data storage possibly affects HDD research. Combining theoretical research with correlation analysis it can be assumed that there is a relation between these two variables, however not a direct one. The authors have established that current data storage technologies are approaching their theoretical limitations, therefore researchers are focusing on finding alternative data storage technologies. Knowing that, it can also be assumed that science focus is shifting from HDD technologies research towards alternative ones, however not necessarily towards DNA data storage technology alone.

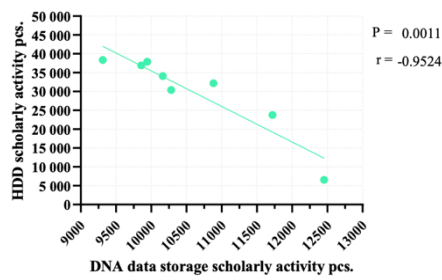


Figure 3. Correlation analysis of DNA data storage scholarly activity and HDD scholarly activity in the period of 2014-2021.

3.2. Comparative analysis of DNA data storage and HDD technologies patenting activities

The direct link towards commercialisation is patenting activities. Therefore, a comparative analysis of DNA data storage and HDD technologies patenting activities has been conducted. Figure 4 reveals a significant difference in patenting activities between DNA data storage and HDD technologies. HDD patenting activity is 156.027-fold higher from 2000 through 2021 than DNA data storage technologies. The results of the literature analysis and comparative analysis of this research suggest that HDD technology is indeed a well-established and commercially active technology. Furthermore, indicating approximations for DNA data storage patenting activities to be considered a well-established technology in the data storage market.

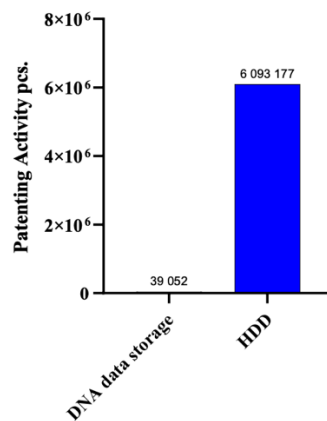


Figure 4. The total patenting activity of DNA data storage and HDD technology between 2000 and 2021.

Looking into the distribution of each technology patenting activity during the period of 2000-2021 in Figures 5a and 5b, a similar upwardly increasing trend is defined. DNA data storage patenting activity has increased 4.432-fold comparing year 2000 and year 2021, whereas HDD technologies patenting activity has increased 8.354-fold during the same timeframe. Suggesting that increasing patenting activity can potentially benefit commercialisation process of DNA data storage technology.

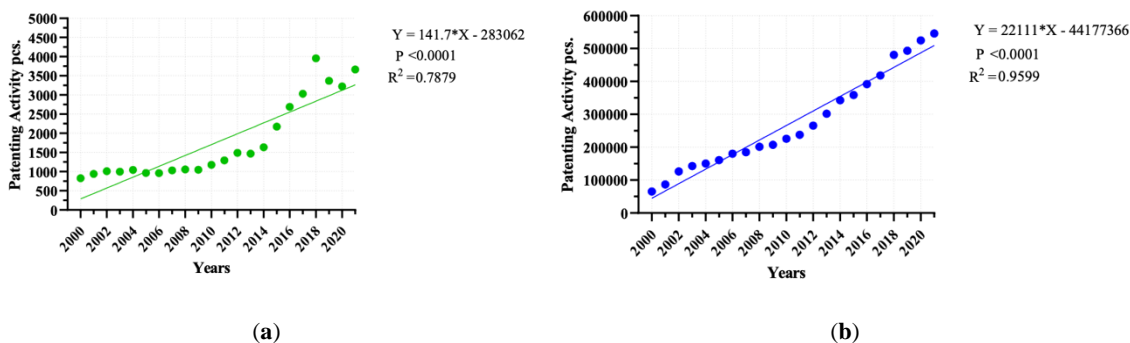


Figure 5. (a) The patenting activity of DNA data storage between 2000-2021. (b) The patenting activity of HDD technology between 2000-2021.

Upon further investigation of patent activities, the top 20 owners of patent activities have been analysed. Not surprisingly most of the top 20 HDD patent activity owners are global and well-known tech/IT companies with IBM having the most patent activities related to HDD technology (figure 6a). However, upon looking into the top 20 owners of patent activities related to DNA data storage technology (figure 6b) the authors encounter that 18 of 20 companies are also tech/IT corporations and only 2 companies represent the biotech industry (Life Technologies Corporation; Ion Torrent Systems Incorporated).

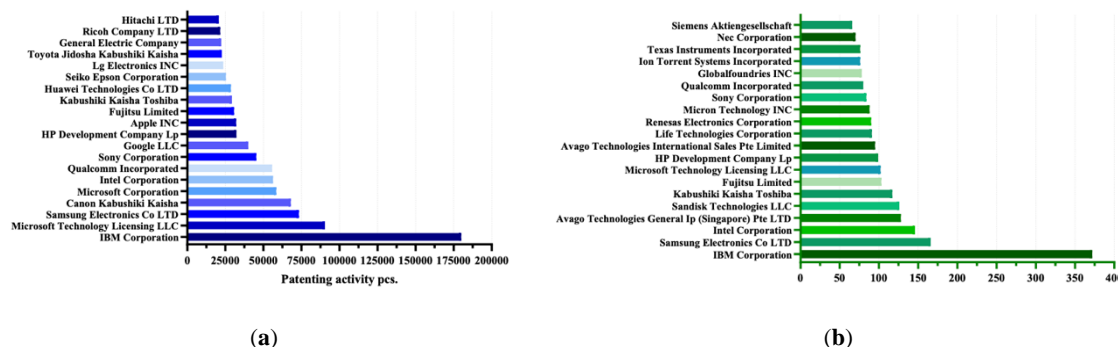


Figure 7. (a) Top 20 owners of HDD patenting activity. (b) Top 20 owners of DNA data storage patenting activity.

While further developing the research similarities between the top 20 HDD patenting activities owners and DNA data storage patenting activities owners (figure 8), the analysis showed that 9 out of 20 (45%) top HDD patenting activities owners are also 9 out of 20 (45%) DNA data storage patenting activities owners. This indicates the transdisciplinary interest and global companies' acknowledgment of DNA data storage technologies' potential for commercialisation and shifting focus from contemporary HDD storage towards DNA data storage is identified.



Figure 8. Relationship map between top 20 patent activity owners of HDD technology and DNA data storage technology.

3.3. Comparative analysis of DNA data storage scholarly activity and patenting activity

After establishing general similarities between DNA data storage and HDD technologies scholarly activities and patent activities the authors continued the analysis concentrating solely on DNA data storage. Theoretical analysis has indicated that the amount of patent activity should directly correlate with the amount of research activity. The authors' analysis has shown that, in the case of DNA data storage, this is indeed the case. Research activity shows a strong positive correlation with patenting activity ($r=0.93, P<0.0001$) (Figure 9) meaning that with an increasing focus on DNA data storage research, patenting activity is likely to rise, fostering rapid commercialisation. As would be expected, the number of papers being published significantly exceeds the number of patents, as patent protection would be inappropriate for a large proportion of DNA nanotechnology research, including valuable studies on fundamental principles.

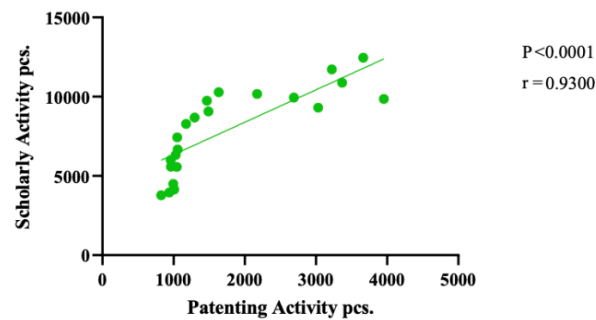


Figure 9. Correlation analysis of DNA data storage scholarly activity and patenting activity.

3.3. Comparative analysis of DNA data storage scholarly activity and patenting activity

Scholarly activity is an important part of DNA data storage commercialisation, and governmental funding is a crucial catalyst for biotech innovations such as DNA data storage technology during the Valley of Death stage. While comparing scholarly activity within the US and EU it was found that the US demonstrates higher levels of scholarly output, averaging 853.77 scholarly activities per year more compared to the EU (figure 10). Although, linear regression analysis showed an upward increase in scholarly activity both in the EU from 705 activities in the year 2000 to 2412 activities in the year 2021 ($R^2 = 0.9781$, $P < 0.0001$) and in the US from 1351 activities in the year 2000 to 2978 activities in the year 2021 ($R^2 = 0.8992$, $P = < 0.0001$). Further indicates a steady upward trend in both regions during the mentioned period, as well as the importance of both regions' participation in further development of DNA data storage technology since the US and EU are the top 2 global leaders in DNA data storage scholarly output.

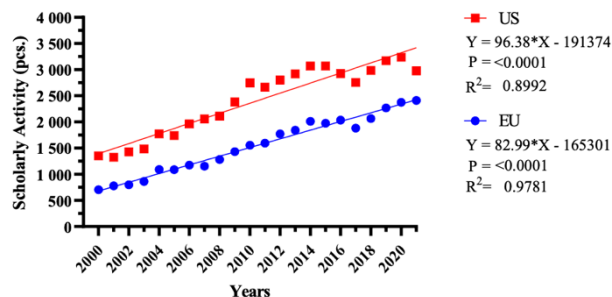


Figure 10. Linear regression analysis of DNA data storage scholarly activity within the US and EU.

However, to understand the difference in scholarly output between the US and EU it is important to investigate governmental financial support and contribution towards DNA data storage. Analysis of data from the OECD database for science, technology and innovation indicated an increase in overall governmental expenditure toward R&D activities between the years 2000 and 2019 (Figure 11). Nonetheless, the US demonstrates higher yearly expenditure toward science, technology and innovation compared to the EU. On an annual average, the US spends 22 645 million \$ more compared to the EU. With the biggest expenditure gap being in the year 2009 – 37 490 million \$. However, the EU has been steadily increasing its funding for Science, Technology and Innovation. From 93 840 million \$ in 2009 to 129 641 million \$ by the year 2019, thereby decreasing the gap between the US and the EU to 10 578 million \$.

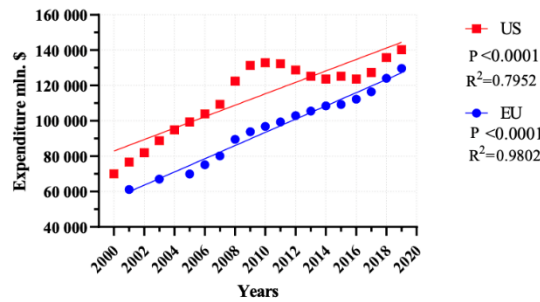


Figure 11. Linear regression analysis of governmental annual expenditure for science, technology and innovation within the US and EU.

Consequently, correlation analysis was conducted to identify if the increase in governmental funding had influenced the growth of scholarly activity in the US and EU. Both the EU and the US established a strong, positive correlation, indicating that an increase in governmental expenditure for science, technology and innovation has a positive increase in DNA data storage scholarly activity (Figure 12). Overall, the US has higher annual funding for developing technologies such as DNA data storage. However, the US has also developed a technology-specific funding programme: the Defence Advanced Research Projects Agency (DARPA), the Intelligence Advanced Research Projects Activity (IARPA), and the National Science Foundation (NSF) provide considerable financing opportunities. Fortunately, positive changes are seen in the EU research funding programs landscape. European Innovation Council has launched a new funding programme “Pathfinder Challenge: DNA- based digital data storage” in 2022, with a budget of 183 million euros.

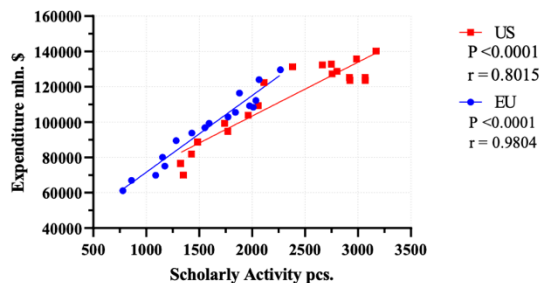


Figure 12. Correlation analysis of governmental expenditure for Science, Technology and Innovation and scholarly activity of DNA data storage within the US and EU.

Further on, while analysing patenting activity in the US and EU (Figure 13) no significant increase between years 2000 and 2021 has been noticed in both regions. Suggesting that the increase in patenting activity observed between 2010 and 2021 happened in different regions like China where patenting activity rose from 19 activities in year 2000 to 2735 activities in 2021. However, upon further comparison of the US and EU it has been established that despite no significant rise in patenting activity, the US still demonstrates higher activity of patenting with an annual average of 373.909 patenting activities more than the EU.

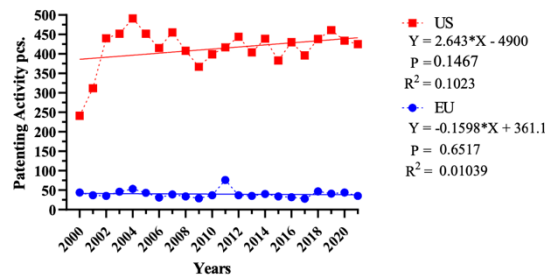


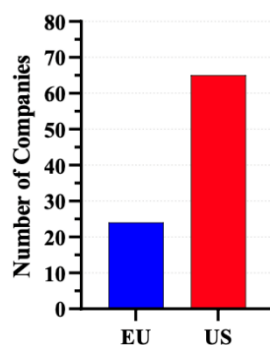
Figure 13. Linear regression analysis of patenting activity within the US and EU.

Lastly, data regarding commercially active companies contributing towards DNA data storage technology development has been analysed (n = 89) and there is a variety of involvement in the DNA data storage commercialisation process (Table 1). Just like in the earlier analysis, the US demonstrates the overall higher number of commercially active companies (n = 65) involved in DNA data storage commercialisation compared to the EU (n = 24). Furthermore, comparing the US to the EU on a level of involvement basis, US demonstrates a higher number of companies in level 1 (n = 18), level 2 (n = 21), and level 3 (n = 26), compared to EU level 1 (n = 9), level 2 (n = 12), level 3 (n = 3) (Figure 14). Indicating the US’s overall success in developing and attempting to commercialise DNA data storage technology compared to the EU. The analysis also demonstrates the involvement of both tech (n = 39) and biotech (n = 50) industries towards DNA data storage commercialisation.

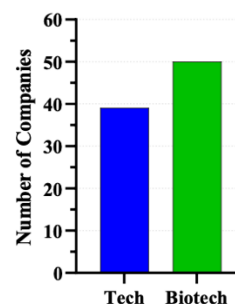
Since DNA data storage technology is primarily biotech industry innovation the higher number of biotech companies is understandable, compared to tech companies. It is observed, that biotech companies are more involved in the direct commercialisation of DNA data storage on level 1 (n = 21) and developing components or parts of DNA data storage process on involvement level 2 (n = 25) compared to tech companies on level 1 (n = 6) and level 2 (n = 8). However, tech companies demonstrate higher numbers on level 3 (n = 25) compared to biotech (n = 4). Indicating tech industries’ interest and support for the development of the technology through indirect measures like patenting, funding and consulting.

Table 1. Company classification according to region, industry and level of involvement in commercialisation of technology.

		Level of Involvement		
	Region	Level 1	Level 2	Level 3
Tech	EU	3	2	3
	US	3	6	22
Biotech	EU	6	10	0
	US	15	15	4



(a)



(b)

Figure 14. (a) Number of companies in EU and US. (b) Number of companies operating in Tech and Biotech industries.

4. Conclusions

This section is not mandatory but can be added to the manuscript if the discussion is unusually long or complex.

Even though overall research of DNA data storage technology is increasing globally with leading regions of the US and the EU, and proof of concepts are already developed showing practical possibilities of the technology, more research and development input is needed for DNA data storage to become a viable and scalable technology, capable of taking over magnetic storage media like HDD.

While comparing DNA data storage scholarly activity with HDD scholarly activity by decades it was established that HDD had a higher overall activity from the year 2000 up to the year 2020 with DNA data storage taking the lead in the year 2021. With correlation analysis it was concluded, that in the second decade from the year 2014 first steps in replacing HDD technology were already visible since scholarly activity on HDD has started its decrease, being replaced by alternative data storage innovations like DNA data storage technology research. Indicating a technological shift within the data storage market shortly.

Patenting activity analysis of DNA data storage and HDD showed absolute leadership of HDD technologies patenting activities for the two decades since 2000. However, research has also shown a constant increase in DNA data storage patenting activity and highlighted similarities to HDD technologies patenting activity pattern, meaning, that DNA data storage patenting activity demonstrates similar behaviour as already established technologies like HDD patenting activity.

Correlation analysis of DNA data storage scholarly activity and patenting activity showed a strong positive correlation proving, that increasing scholarly activity is directly increasing patenting activities resulting in increasing commercial activity of the technology. Moreover, discovering that 45% of the top patenting activity owners of HDD technology are also among the top 20 for DNA data storage technology – mostly big tech corporations – suggests that scientific activities will continue to increase. As the active interest and patent activity ownership indicate the increasing interest of the tech industry and further transdisciplinary partnership development between tech and biotech industries towards the successful commercialisation of DNA data storage technology.

The US output of scholarly and patenting activities has shown to be significantly higher than the EU same as governmental funding for the science, technology and innovation sector. Correlation analysis revealed that increased governmental funding for the science, technology, and innovation sector strongly correlates with DNA data storage scholarly activity. This explains the US's leadership in this field and underscores the importance of governmental support in developing DNA data storage technology. Furthermore, showing the necessity of technology-specific funding like IARPA's Molecular Information Storage Technology (MIST) initiative to further catalyse the development of DNA data storage technology and invite other countries to create similar initiatives according to good practices already established.

Biotech companies are primarily involved in the development of DNA data storage technologies, but there is an increasing interest from tech companies as well. Involvement of the tech industry with high monetary values and ability to provide funding for commercialisation of DNA data storage technology led to the creation of transdisciplinary organisations like “DNA data storage alliance”, connecting large companies from tech, biotech industries, universities, and venture capital companies striving towards the same commercialisation goals. This enabled companies like DNA Script and Illumina to be among the first to participate in governmental programs like IARPA's Molecular Information Storage Technology (MIST) initiative which intends to create systems that can write 1 TB and read 10 TB of data per day using DNA.

Therefore, transdisciplinary cooperation model should be considered for further DNA data storage development. This model facilitates the transfer of crucial insights and data from tech industry market experts to biotech companies focused on researching and developing DNA data storage. Incorporates universities, that have the freedom to conduct more risk-worthy research, but at the same time, together with industry experts, maintain focus on technologies commercial viability and scalability, develop market and consumer-oriented product.

However, more transdisciplinary alliances and ecosystems are required to minimise the chance of technological monopolisation and increase competitiveness within DNA data storage commercialisation allowing the technology to avoid the “valley of death”. Finally, it is also defined that increasing the number of transdisciplinary alliances will result in faster commercialisation and higher funding capabilities.

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