CTE Workshop Proceedings, 2025, Vol. **12**, pp. 270–284 https://doi.org/10.55056/cte.765

Digital learning environments and bioethical reasoning: A study of biology students' engagement with human enhancement ethics

Elena V. Komarova

Independent researcher, Moscow, Russia

Abstract. This study examines how digital learning environments shape biology students' bioethical reasoning, focusing particularly on perceptions of biotechnological human enhancement. As technological advances in gene editing coincided with the global pandemic, both events catalyzed significant changes in biological education and highlighted the importance of bioethical understanding. Through a survey of 80 students at different educational levels, we explored how exposure to bioethical content in digital educational settings influenced students' ethical reasoning about emerging biotechnologies. Our findings reveal that students who experienced interactive and dialogic digital learning formats demonstrated more nuanced ethical positions, with greater recognition of social implications and potential risks of biotechnological enhancements. The research provides insights into how technological mediation of bioethics education shapes value formation in biology students and suggests strategies for effective digital pedagogical approaches when teaching complex bioethical topics. These findings have significant implications for technology-enhanced biology education during and beyond crisis periods, particularly for preparing future biologists to navigate complex ethical landscapes in their professional practice.

Keywords: digital learning environments, bioethical reasoning, human enhancement, biotechnology education, genome editing, ethical decision-making, educational technology, value formation, interactive pedagogy, biology students

1. Introduction

The beginning of 2020 brought unprecedented global challenges that transformed both biological science and educational practice. The COVID-19 pandemic accelerated biological research while simultaneously forcing educational institutions to rapidly transition to digital learning environments [1]. Concurrently, advances in biotechnology – particularly the award of the 2020 Nobel Prize in Chemistry to Emmanuelle Charpentier and Jennifer Doudna for their groundbreaking CRISPR/Cas9 genetic scissors – raised profound bioethical questions about human enhancement and genome editing [10]. This confluence of events created a unique moment for examining how digital learning environments influence students' bioethical reasoning about cutting-edge biological technologies.

Biological education sits at a critical intersection where scientific knowledge, values formation, and now technological mediation converge. The integration of bioethical content into biology curricula has long been recognized as essential for preparing students to navigate complex moral landscapes [8], but less understood is how the transition to digital learning environments affects this formative process. As Bryzgalina [4] notes, the emerging field of "digital bioethics" offers new frameworks for understanding these intersections, highlighting both technological applications in bioethics research and ethical considerations surrounding digital health technologies.

0000-0002-3476-3351 (E. V. Komarova)
komarova1978@mail.ru (E. V. Komarova)

This study examines how digital learning environments influence biology students' bioethical reasoning, with a particular focus on perceptions of human enhancement technologies. Our research was driven by three primary questions: (1) How does exposure to bioethical content in digital biology education influence students' ethical reasoning about biotechnological enhancement? (2) What differences emerge in bioethical reasoning between students who experienced different digital pedagogical approaches? (3) How do students' preferences for technological learning formats correlate with their bioethical positions?

While previous studies have explored various aspects of bioethics education [5, 7] and digital learning environments [13], few have examined the intersection of these domains, particularly in the context of biology education during global crises. This research addresses this gap by providing empirical insights into how digital learning environments shape bioethical reasoning in biology students, with implications for both educational technology implementation and bioethics pedagogy.

The paper is structured as follows: first, we establish a theoretical framework linking educational technology with bioethical value formation. We then review relevant literature on digital approaches to bioethics education. After describing our methodology, we present findings on students' bioethical reasoning and correlations with digital learning experiences. The discussion section interprets these findings through an educational technology lens, followed by implications for practice and recommendations for future research.

2. Theoretical framework

2.1. Educational technology and value formation

The relationship between educational technology and values formation rests on the understanding that learning environments – whether physical or digital – play a crucial role in shaping not only what students learn but how they process, evaluate, and integrate knowledge into their value systems. As Pavarini et al. [12] suggest, digital tools for bioethics education must align with theoretical frameworks that integrate context, narrative, and embodiment in moral decision-making.

Our theoretical approach draws on the culturological theory of education content [3], which posits that educational outcomes include not only knowledge and reproductive experience, but also creative activity experience and emotional-value attitudes. Within this framework, we consider the experience of emotional-value attitudes – particularly as mediated through digital learning environments – as a critical, system-forming element that shapes students' bioethical reasoning.

This approach aligns with recent work on "design bioethics" [12], which argues that purpose-built digital tools can engender situated engagement with bioethical questions, achieve such engagement at scale, and access groups traditionally under-represented in bioethics research. We extend this framework by examining how various digital learning environments and pedagogical approaches differently influence bioethical reasoning about human enhancement technologies.

2.2. Digital bioethics education models

The emerging concept of "digital bioethics" provides a useful framework for our investigation. As described by Bryzgalina [4], digital bioethics encompasses both the use of digital methods for empirical bioethics research and the ethical evaluation of digital health technologies. This dual focus mirrors our research interests in both how digital technologies mediate bioethics education and how students reason about emerging biotechnologies.

Within this framework, we distinguish between several models of digital bioethics education that vary in their level of student engagement and technological integration:

1. Information-transmission models that utilize digital platforms primarily for content delivery.
2. Dialogic models that leverage technology to facilitate discussion and collaborative meaning-making.
3. Experiential models that use technologies such as simulations or case-based scenarios to contextualize ethical dilemmas.
4. Integrated models that combine multiple technological approaches with varied pedagogical strategies.

These models provide a theoretical basis for understanding how different digital learning environments might influence the development of bioethical reasoning. Our research examines which models prove most effective for facilitating sophisticated ethical reasoning about human enhancement technologies.

3. Literature review

3.1. Digital approaches to bioethics teaching

Recent literature demonstrates growing interest in technology-enhanced bioethics education. Moses et al. [10] describe the development of a web-based bioethics casebook that moves beyond traditional information dissemination to create an immersive, engaging learning experience. Their approach reflects a broader trend toward web-based frameworks that support both self-directed learning and group discussions about bioethical dilemmas.

Similarly, Chashina and Kartanova [6] highlight the effectiveness of visual technologies and problem-based learning in bioethics education. Their research suggests that visual aids such as diagrams and illustrations, when integrated into digital learning environments, help students memorize, analyze, and synthesize bioethical concepts, while also stimulating emotions and creativity. This multi-modal approach aligns with educational technology research suggesting that varied representational forms enhance comprehension of complex concepts [16].

The transition to fully online bioethics education accelerated during the COVID-19 pandemic. Al-Kumaim et al. [1] document challenges that emerged during this rapid transition, including information overload, adaptation difficulties, and stress-related issues. However, they also identify motivational factors that supported successful online learning, including personalized pathways, real-time feedback, and gamification elements. These findings suggest that carefully designed digital learning environments can effectively support bioethics education despite challenges.

3.2. Value formation in digital learning environments

Research on how digital learning environments influence value formation remains limited, but several studies offer relevant insights. Alkhnbashi, Mohammad and Bamasoud [2] argue that effective digital learning requires attention to both technical infrastructure and pedagogical approaches. Their work suggests that hybrid models – combining synchronous and asynchronous activities – provide flexibility while supporting meaningful engagement with value-laden content.

Canu et al. [5] specifically examine bioethics education through critical thinking skill development. While not focused exclusively on digital environments, their work demonstrates the importance of authentic cases that bring values into conflict and the effectiveness of peer evaluation in developing reflective abilities. These findings have implications for designing digital learning experiences that foster bioethical reasoning.

More directly relevant to our study, Alkorta and Mujika [3] explore the impact of online learning and AI-based learning on bioethics education. Their findings indicate that online learning significantly impacts bioethics education and that a significant

association exists between AI and bioethics education. They advocate for redesigning bioethics education through AI/VR-based and online learning approaches to provide enriched, interactive classroom experiences.

3.3. Technology-enhanced assessment of ethical reasoning

Digital assessment of ethical reasoning presents both opportunities and challenges. Keskin-Samanci, Özer Keskin and Arslan [9] describe the development of a "bioethical values inventory" for secondary education students, demonstrating the potential for structured assessment tools to reveal ethical values in decision-making. While their work did not specifically address digital implementations, it provides a foundation for developing technology-enhanced assessment approaches.

More recently, Sleigh et al. [15] conducted a systematic mapping of digital tools designed for ethical deliberation and decision-making. Their research identifies key features and mechanisms that facilitate ethical reasoning, offering insights for both tool development and implementation. Similarly, Siddiq and Murchan [14] highlight the need for ethical guidelines when using technology-enabled data and analytics in educational assessment, particularly regarding privacy and equity concerns.

These studies collectively point to both the potential of digital tools to enhance bioethics education and the importance of thoughtful implementation that addresses technical, pedagogical, and ethical considerations. Our research builds on this foundation by examining how different digital learning experiences influence biology students' bioethical reasoning about human enhancement technologies.

4. Methodology

4.1. Research context

This study was conducted at the Immanuel Kant Baltic Federal University during the 2020-2021 academic year, a period marked by both the COVID-19 pandemic and significant advances in biotechnology. The university's biology curriculum includes several courses with bioethical content, notably "Fundamentals of Theoretical Biology" (72 hours) for fourth-year biology students and "Bioethics" (60 hours) for fifth-year biotechnology and bioengineering students. These courses were delivered primarily through digital learning environments during the study period due to pandemic-related restrictions.

4.2. Participants

The study included 80 students from the Institute of Living Systems, distributed across three groups:

- Group 1: 57 first-year students in biology, chemistry, biotechnology, and bioengineering programs who had not yet taken courses with substantial bioethical content.
- Group 2: 14 fourth-year biology students who had completed the "Fundamentals of Theoretical Biology" course, which included bioethical topics delivered through a combination of online lectures and interactive activities such as round tables and essay assignments.
- Group 3: 9 fifth-year biotechnology and bioengineering students who had completed the "Bioethics" course delivered primarily through online lectures and project presentations.

This distribution allowed for comparison between students with different levels of exposure to bioethical content and different digital learning experiences.

4.3. Survey instrument

Data was collected through an online survey titled "Biology and Ethics of Human Improvement" using Google Forms. The survey included both closed and open-ended questions designed to assess students' understanding of bioethical issues related to human enhancement technologies and their preferences for different learning formats. Key questions addressed:

- Perceptions of human biotechnological enhancement as a viable project
- Ethical considerations regarding human genome editing
- Assessment of potential dangers associated with biotechnological enhancement
- Views on public discourse about enhancement technologies
- Preferences for learning formats (lectures, round tables, webinars, independent reading)
- Word associations with "human improvement"

The survey was designed to reveal not only students' bioethical positions but also correlations between these positions and their digital learning experiences.

4.4. Data analysis

Survey responses were analyzed using both quantitative and qualitative approaches. Quantitative analysis included descriptive statistics to identify patterns and differences between student groups. For open-ended responses, particularly the word association question, we conducted lexical-semantic analysis to identify patterns in language use that might reflect underlying value structures.

The analysis focused specifically on identifying correlations between students' bioethical reasoning patterns and their experiences with different digital learning environments and formats. We examined both the content of students' ethical positions (what they believed) and the structure of their reasoning (how they justified their positions).

5. Results

5.1. Digital learning experiences and ethical positions on human enhancement

Our analysis revealed significant differences in bioethical reasoning between student groups that had experienced different digital learning environments. Figure 1 shows students' responses regarding whether human improvement can be considered a viable biotechnological project.

Notably, fifth-year students who had completed the "Bioethics" course demonstrated greater caution in their assessment, with only 22.2% choosing "unequivocally yes" compared to 43.9% of first-year students and 50% of fourth-year students. This suggests that the specific digital learning environment of the "Bioethics" course – characterized by online lectures and project presentations – may have fostered a more cautious approach to biotechnological enhancement.

More striking differences emerged when students were asked about the ethical acceptability of human genome editing (figure 2). Fourth-year students who had experienced the "Fundamentals of Theoretical Biology" course, with its emphasis on interactive discussions through round tables and essay assignments, showed the most skepticism, with only 7.1% responding "unequivocally yes" compared to 36.8% of first-year students and 44.4% of fifth-year students.

This pattern suggests that the dialogic, interactive digital learning environment experienced by fourth-year students may have developed more critical ethical reasoning about biotechnological interventions. The structure of the "Fundamentals of Theoretical Biology" course – which included watching and discussing films with bioethical themes and writing reflective essays – appears to have fostered deeper

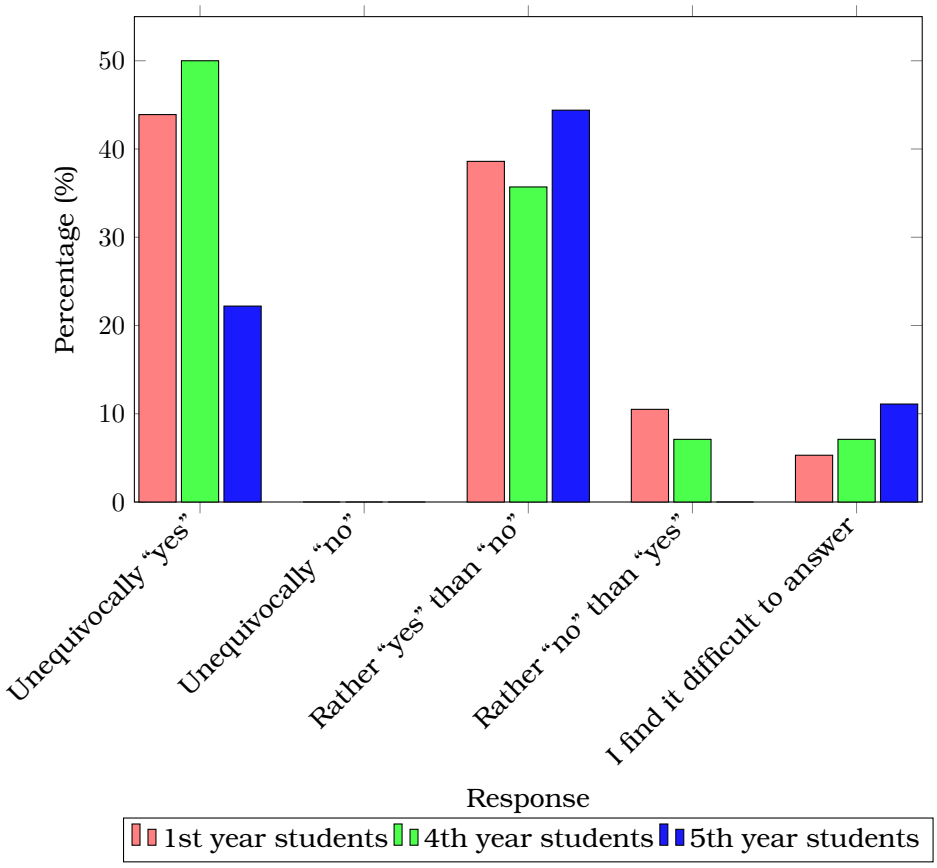

Figure 1: Responses to "Do you think that human improvement can be a modern biotechnological project?"

consideration of ethical implications compared to the more information-transmission approach of the "Bioethics" course.

5.2. Perceptions of risks associated with human enhancement

Further differences emerged in students' assessment of potential dangers associated with biotechnological enhancement (figure 3). While all student groups identified biological consequences as a significant concern, fourth-year students placed greater emphasis on social risks such as inequality and elitism associated with enhanced genomes.

Notably, fourth-year students were much more likely to identify "a person's loss of self-sufficiency as a natural phenomenon" as a danger (57.1%) compared to first-year (19.3%) and fifth-year (11.1%) students. This suggests a more holistic view of human nature that considers not just physical but existential implications of enhancement technologies – a perspective that appears to have been fostered by the interactive, discussion-based digital learning environment they experienced.

These differences in risk perception align with differences in views on the potential of genome editing (figure 4). While most students across all groups believed genome editing would solve previously intractable problems, a substantial proportion of fourth-year students (28.6%) also viewed it as a potential mechanism for increasing social inequality – a perspective rarely expressed by first-year (3.5%) or fifth-year (0%) students.

5.3. Learning format preferences and bioethical reasoning

Our analysis revealed correlations between students' preferred learning formats and their bioethical reasoning patterns. Figure 5 shows the distribution of format

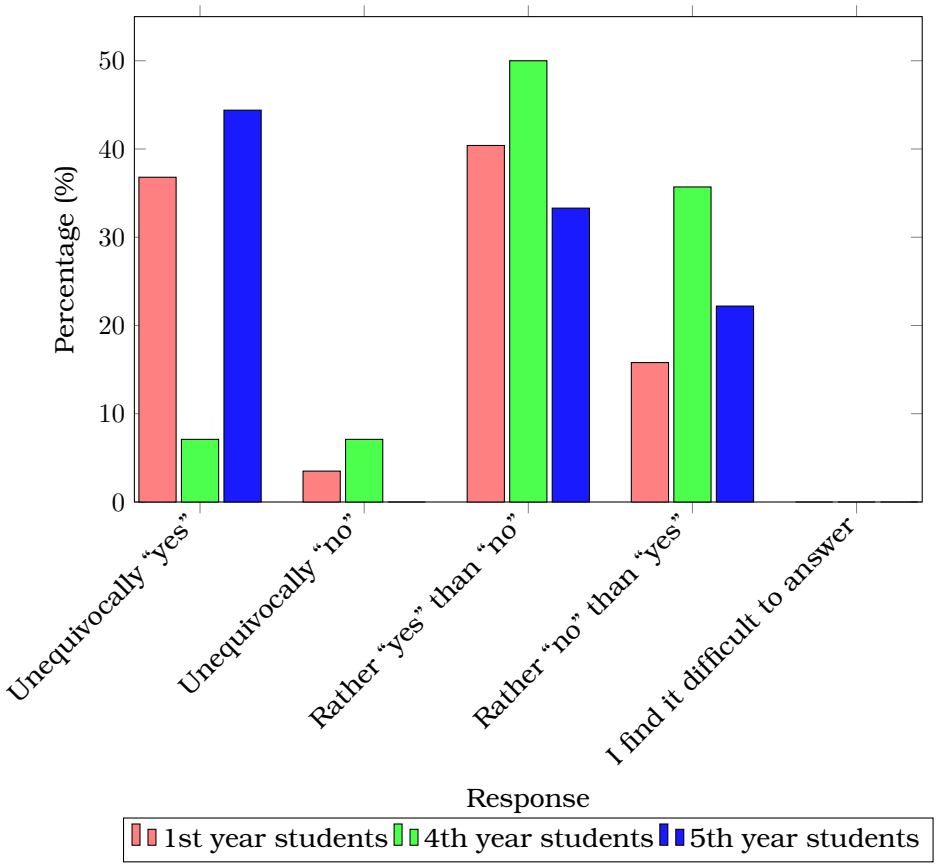

Figure 2: Responses to "Do you consider it possible from an ethical point of view to intervene in the human genome, edit it?"

preferences across student groups.

A clear trend emerges from first-year to fifth-year students: the preference for monologic teaching methods (lectures) decreases while the preference for dialogic methods (round tables) increases. This shift appears to correlate with more nuanced ethical reasoning, as students who preferred dialogic formats were also more likely to identify social and existential risks associated with enhancement technologies.

This correlation suggests that experience with interactive digital learning environments may not only shape bioethical reasoning but also influence preferences for future learning experiences. Students who had engaged in discussion-based digital learning appeared to recognize its value for navigating complex ethical questions, perhaps because these formats better support the contextual, narrative, and embodied aspects of moral decision-making highlighted in our theoretical framework.

5.4. Word associations and bioethical reasoning patterns

The open-ended question asking students to name three words associated with "human improvement" provided insights into underlying conceptual frameworks. Table 1 presents a categorized summary of responses.

First-year students, who had not yet experienced bioethics education in digital environments, used more scientific and technical terms, suggesting a focus on the procedural aspects of enhancement. Fourth-year students, who had experienced interactive digital bioethics education, included more negative associations and social implications. Fifth-year students, while fewer in number, showed a more practical, application-oriented vocabulary.

Notably, words with negative connotations were least common among first-year

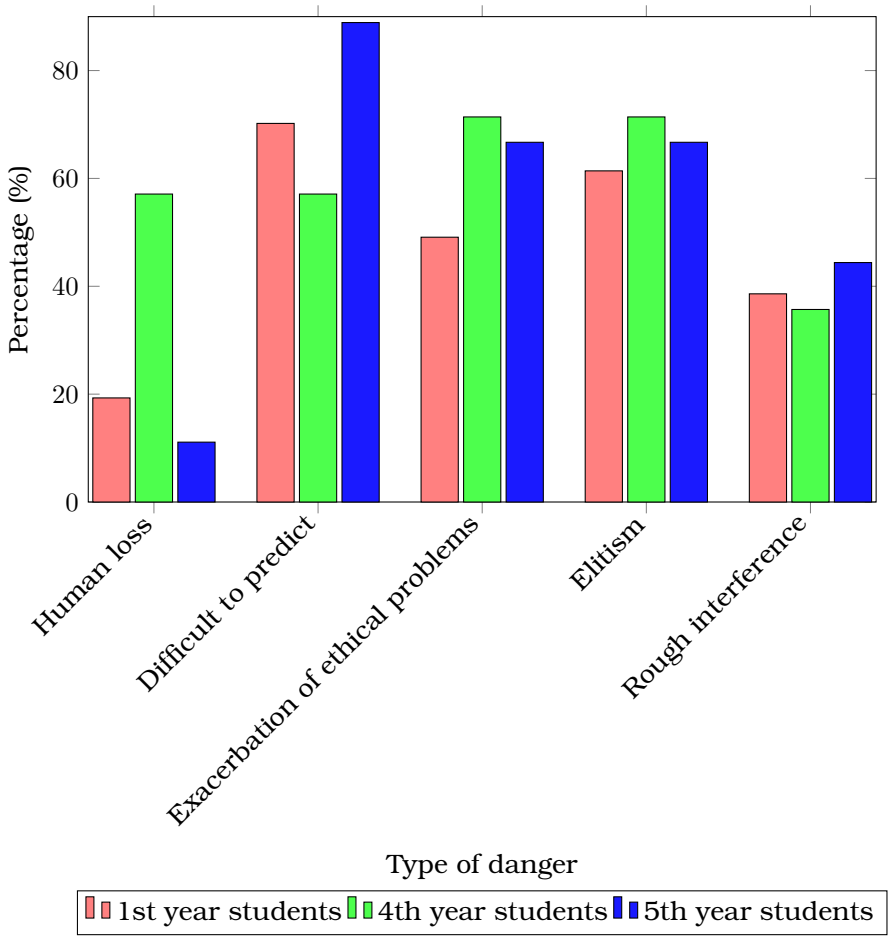

Figure 3: Responses to "What kind of danger can occur when trying to biotechnological enhancement of a person?"

students (8%) and most common among fourth-year students (18.8%). This pattern aligns with our other findings suggesting that interactive digital learning environments foster more critical ethical reasoning about biotechnological enhancement.

6. Discussion

6.1. The influence of digital learning environments on bioethical reasoning

Our findings suggest that different digital learning environments significantly influence how biology students reason about bioethical issues related to human enhancement. The data reveal a correlation between exposure to interactive, dialogic digital learning formats and the development of more nuanced, socially contextualized ethical reasoning. This aligns with argument by Pavarini et al. [12] that digital bioethics tools are most effective when they support contextualized, narrative-based engagement with ethical questions.

The fourth-year biology students, who experienced a digital learning environment characterized by round-table discussions, essay writing, and collective film analysis, demonstrated the most sophisticated ethical reasoning about human enhancement. Their responses more frequently acknowledged social risks such as inequality and existential concerns such as human self-sufficiency. This suggests that interactive digital formats may better support the development of what Canu et al. [5] describe as critical thinking and reflective abilities in bioethics education.

In contrast, fifth-year biotechnology students, who experienced a more lecture-focused digital environment, demonstrated greater technical knowledge but less

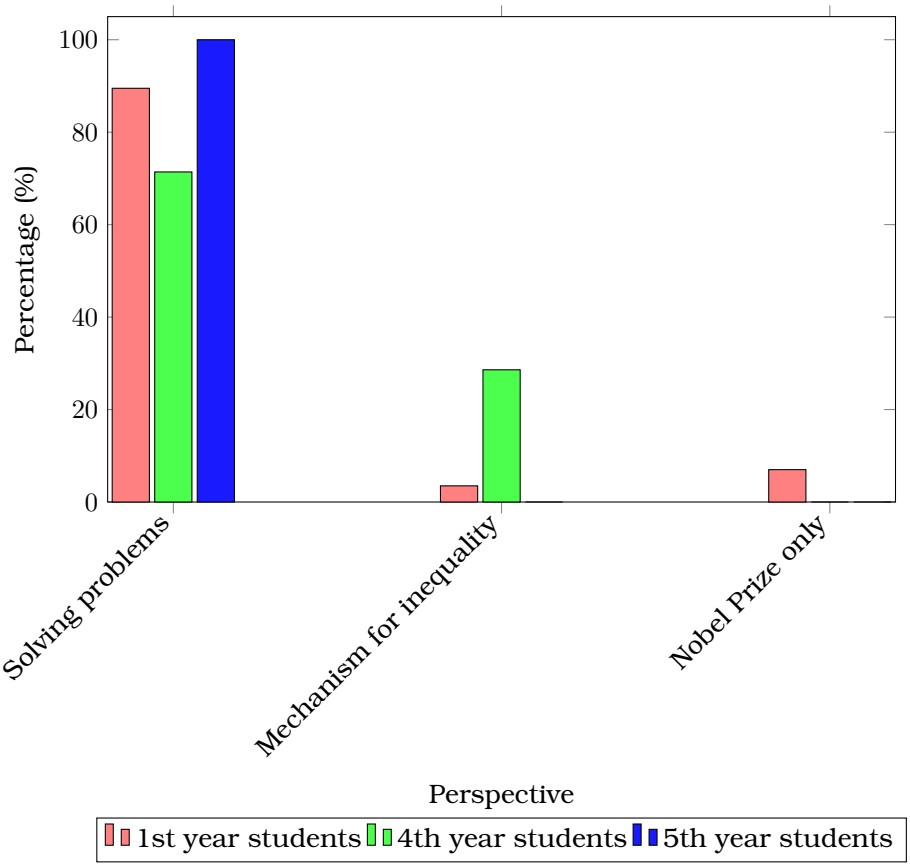

Figure 4: Responses to "In your opinion, the possibility of genome editing is:"

Table 1
Categorized word associations with "human improvement".

Category	1st year students	4th year students	5th year students
Scientific terms	Genetics, genome, DNA, biotechnology, bioengineering	Biotechnology, neurointerface, immunity	CRISPR/Cas, genome
Positive outcomes	Immortality, longevity, perfection, strength, health	Health, ideality, progress	Cure, adaptation, upgrade
Technical aspects	Cyborg, brain-computer interfaces, chip, prosthesis	Prosthesis, technology	Botox, liposuction
Negative associations	Social stratification, break, vice, emperor	End of the world, against nature, regression, inaccessibility	Not now, what will God say?
Complex concepts	Transhumanism, evolution, posthumanism	Ethics, bioethics	Eugenics, risks

critical perspective on enhancement technologies. Their responses focused primarily on scientific and practical considerations, with less attention to social or existential implications. This finding supports argument by Chashina and Kartanova [6] that bioethics education requires not only information transmission but also emotional engagement and creative thinking – elements that may be better supported by interactive

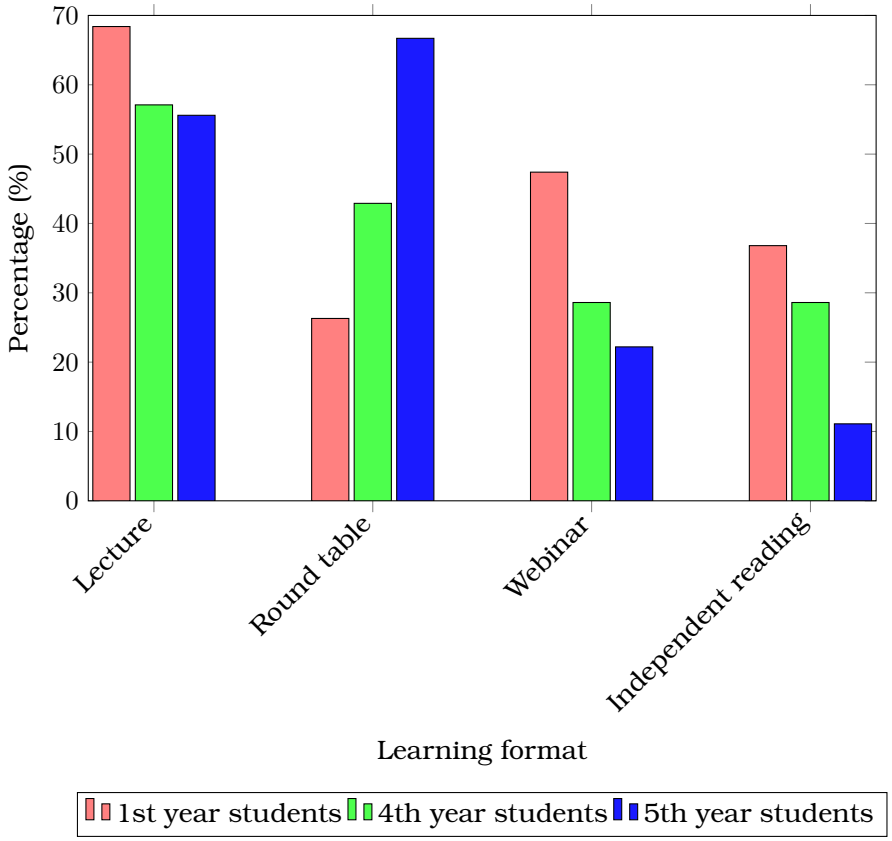

Figure 5: Responses to "In what form would you like to learn more about enhancement?"

digital formats.

These observations align with the theoretical models of digital bioethics education outlined in our framework. The fourth-year students' experience most closely resembled the dialogic and experiential models, while the fifth-year students' experience aligned more with the information-transmission model. Our findings suggest that the integrated and dialogic models may be more effective for developing sophisticated bioethical reasoning, particularly regarding complex issues like human enhancement.

6.2. Technology mediation and value formation

Our research suggests that technology does not simply deliver content but actively mediates how students engage with and integrate bioethical knowledge into their value systems. The differences in bioethical reasoning between student groups cannot be attributed solely to content exposure, as both fourth-year and fifth-year students had studied bioethical topics. Rather, the differences appear to correlate with how technology mediated their learning experiences – whether as a platform for information transmission or as a tool for dialogue and reflection.

This finding supports the perspective of Alkorta and Mujika [3] that online learning significantly impacts bioethics education. Our results extend this work by suggesting that the specific implementation of digital learning – not just its presence – shapes outcomes. Interactive digital environments that support discussion and reflection appear more effective in developing critical bioethical reasoning than those focused primarily on content delivery.

The shift in learning format preferences from monologic to dialogic approaches as students progress through their education further suggests that experience with interactive digital learning influences how students conceptualize effective bioethics

education. This points to a potential virtuous cycle wherein exposure to dialogic digital learning environments both develops critical reasoning skills and fosters appreciation for interactive educational approaches.

6.3. Implications for educational technology in bioethics education

Our findings have several implications for the design and implementation of educational technology in bioethics education. First, they suggest that technology should be leveraged not merely for content delivery but for creating interactive spaces where students can engage in dialogue about complex ethical issues. This aligns with emphasis by Moses et al. [10] on web-based tools that support both individual exploration and group discussion.

Second, our results indicate that effective digital bioethics education should incorporate real-world cases and scenarios that highlight value conflicts. The fourth-year students' exposure to bioethical films and case studies appears to have fostered more nuanced ethical reasoning than the more abstract approach experienced by fifth-year students. This supports recommendation by Alkorta and Mujika [3] for AI/VR-based and online learning approaches that provide enriched, interactive classroom experiences.

Third, our findings suggest the importance of assessment approaches that capture the complexity of bioethical reasoning. Simple knowledge tests may not adequately reveal whether students have developed the critical thinking and reflective abilities needed to navigate complex ethical landscapes. More sophisticated assessment tools, such as the bioethical values inventory described by Keskin-Samanci, Özer Keskin and Arslan [9], may be necessary to evaluate the outcomes of digital bioethics education.

Finally, our results highlight the potential value of blended approaches that combine different digital learning formats and pedagogical strategies. The most effective bioethics education may not rely exclusively on any single format but rather integrate lectures, discussions, case analyses, and reflective writing in a coherent digital learning environment. This aligns with recommendation by Alkhnbashi, Mohammad and Bamasoud [2] for hybrid models that combine synchronous and asynchronous activities.

7. Implications for practice

Based on our findings, we offer several recommendations for implementing educational technology in bioethics education:

7.1. Recommendations for Digital Curriculum Design

Our findings suggest several practical recommendations for designing digital curricula that effectively support bioethical reasoning development:

1. Design digital learning environments that facilitate dialogue rather than merely transmitting information. Discussion forums, virtual round tables, and collaborative annotation tools can support the social construction of bioethical understanding.
2. Use films, videos, and interactive scenarios that present authentic bioethical dilemmas. These materials provide context and emotional engagement that text-only resources may lack.
3. Combine real-time discussions with reflective writing activities that allow students to process complex ethical issues at their own pace.
4. Digital resources should represent multiple viewpoints on bioethical issues, including scientists, ethicists, policymakers, and potentially affected populations.

5. Design assessment approaches that capture the development of ethical reasoning, not just knowledge acquisition. Digital portfolios, case analyses, and peer evaluation can provide richer insights than traditional tests.

These recommendations align with emphasis by Parder et al. [11] on dialogic communication for ethical decision-making and value clarification. By thoughtfully implementing these approaches, educators can leverage digital technologies to enhance bioethics education rather than simply digitizing traditional content delivery methods.

7.2. Suggestions for educator professional development

Effectively implementing technology-enhanced bioethics education requires appropriate preparation for educators. Based on our findings, we suggest the following professional development priorities:

1. Educators need skills for moderating bioethical discussions in digital spaces, including strategies for encouraging participation, managing disagreements, and fostering inclusive dialogue.
2. While deep technical expertise may not be necessary, educators should be comfortable with the digital tools they use and understand their affordances for supporting different types of learning activities.
3. Given the rapid pace of biotechnological advancement, educators need ongoing opportunities to update their understanding of emerging ethical issues, particularly regarding technologies like CRISPR/Cas9 that raise novel questions.
4. Educators should develop skills for designing and implementing assessment approaches that capture the complexity of bioethical reasoning in digital environments.

These professional development priorities align with finding by Van Rooy [16] that when teachers receive appropriate support for integrating digital technologies, they recognize the immediate pedagogical benefits for student learning. Without such support, digital tools may simply replicate traditional information-transmission approaches rather than leveraging technology's potential for interactive, reflective learning.

8. Limitations and future research

8.1. Limitations of the current study

Several limitations should be considered when interpreting our findings. First, the study's cross-sectional design makes it difficult to establish causal relationships between digital learning experiences and bioethical reasoning patterns. The differences observed between student groups may reflect not only their educational experiences but also selection factors, maturation effects, or other variables not captured in our analysis.

Second, the sample size, particularly for the fourth-year (n=14) and fifth-year (n=9) groups, limits the statistical power of our comparisons and the generalizability of our findings. A larger sample would provide more robust evidence for the patterns observed.

Third, our study relied primarily on self-reported data collected through surveys. Direct observation of students engaging with digital learning environments or analysis of their written reflections might provide deeper insights into how these environments influence bioethical reasoning.

Finally, while we examined correlations between digital learning experiences and bioethical reasoning, we did not specifically manipulate the design of digital learning environments to test causal relationships. Experimental or quasi-experimental studies would be needed to more definitively establish the impact of specific digital learning approaches on bioethical reasoning development.

8.2. Future research directions

Based on our findings and limitations, we suggest several directions for future research:

1. Track the development of bioethical reasoning in biology students over time as they engage with various digital learning environments. This approach would provide more compelling evidence for the impact of specific educational experiences.
2. Directly compare the effectiveness of different digital learning environments (e.g., information-transmission vs. dialogic approaches) for developing bioethical reasoning. Such studies could include both self-reported measures and direct assessment of reasoning skills.
3. Combine quantitative measures with qualitative analysis of student discussions, reflections, and assignments to provide deeper insights into how digital learning environments influence bioethical reasoning processes.
4. Design and evaluate specific digital tools for bioethics education, such as interactive case studies, simulations, or collaborative annotation systems. These studies could contribute to both theoretical understanding and practical implementation.
5. Examine how cultural contexts influence the effectiveness of digital approaches to bioethics education. This research could inform more culturally responsive implementations of educational technology.

9. Conclusion

Our study provides empirical insights into how digital learning environments influence biology students' bioethical reasoning about human enhancement technologies. The findings suggest that interactive, dialogic digital approaches foster more nuanced ethical reasoning that considers not only biological but also social and existential implications of biotechnological enhancements. This conclusion aligns with theoretical frameworks emphasizing the importance of context, narrative, and reflection in bioethics education.

The coincidence of the COVID-19 pandemic and advances in genome editing technologies created a unique moment for examining bioethics education in digital environments. Our findings suggest that thoughtfully designed digital learning experiences can effectively support the development of sophisticated bioethical reasoning even during periods of educational disruption. However, the specific implementation of digital learning – not merely its presence – appears crucial for determining educational outcomes.

As biotechnology continues to advance, raising new ethical questions about human nature and societal values, preparing biology students to engage thoughtfully with these questions becomes increasingly important. Our research suggests that educational technology can play a valuable role in this preparation when implemented in ways that support dialogue, reflection, and critical thinking. By using digital tools to create interactive learning environments rather than simply delivering content, educators can help students develop the ethical reasoning capacities needed to navigate complex bioethical landscapes.

Future research should build on these findings to develop and evaluate specific digital approaches to bioethics education, with attention to both technological design and pedagogical implementation. Such work will contribute to both theoretical understanding of how digital environments influence value formation and practical guidance for educators seeking to prepare biology students for the ethical challenges of an increasingly biotechnological world.

References

[1] Al-Kumaim, N.H., Alhazmi, A.K., Mohammed, F., Gazem, N.A., Shabbir, M.S. and Fazea, Y., 2021. Exploring the Impact of the COVID-19 Pandemic on University Students' Learning Life: An Integrated Conceptual Motivational Model for Sustainable and Healthy Online Learning. *Sustainability*, 13(5), p.2546. Available from: https://doi.org/10.3390/su13052546.

[2] Alkhnbashi, O.S., Mohammad, R. and Bamasoud, D.M., 2024. Education in Transition: Adapting and Thriving in a Post-COVID World. *Systems*, 12(10). Available from: https://doi.org/10.3390/systems12100402.

[3] Alkorta, J. and Mujika, M., 2022. Highlighting the role played by distance learning methods in strengthening the bioethics in the biotechnology curriculum in Singapore. *Journal of Commercial Biotechnology*, 27(5), pp.92–103. Available from: https://doi.org/10.5912/jcb1892.

[4] Bryzgalina, E.V., 2023. Digital Bioethics as Digital Health Ethics. *Praxema*, 166(1-35), pp.9–29. Available from: https://doi.org/10.23951/2312-7899-2023-1-9-29.

[5] Canu, M.H., Dehennaut, V., Dupont, E., Pauwels, M. and Bodart, J.F., 2022. Introduction to bioethics through mobilization of critical thinking skills. *International Conference on Higher Education Advances*. vol. 2022-June, pp.11–19. Available from: https://doi.org/10.4995/HEAd22.2022.14463.

[6] Chashina, Z.V. and Kartanova, A.D., 2016. Teaching methodology in the study of bioethics. *Integration of Education*, 20(1), pp.97–104. Available from: https://doi.org/10.15507/1991-9468.082.020.201601.097-104.

[7] Chowning, J.T., Griswold, J.C., Kovarik, D.N. and Collins, L.J., 2012. Fostering critical thinking, reasoning, and argumentation skills through bioethics education. *PLoS ONE*, 7(5), p.e36791. Available from: https://doi.org/10.1371/journal.pone.0036791.

[8] Iancu, M., 2014. Bioethical education component and cornerstone of youth's moral education. *European Journal of Science and Theology*, 10(3), pp.95–102. Available from: http://www.ejst.tuiasi.ro/Files/45/10_Iancu.pdf.

[9] Keskin-Samanci, N., Keskin, M. Özer and Arslan, O., 2014. Development of 'bioethical values inventory' for pupils in secondary education within the scope of bioethical education. *Eurasia Journal of Mathematics, Science and Technology Education*, 10(2), pp.69–76. Available from: https://doi.org/10.12973/eurasia.2014.1029a.

[10] Moses, J., Berlinger, N., Dunn, M.C., Gusmano, M.K. and Chin, J.J., 2015. Bioethics Casebook 2.0: Using Web-Based Design and Tools to Promote Ethical Reflection and Practice in Health Care. *Hastings Center Report*, 45(6), pp.19–25. Available from: https://doi.org/10.1002/hast.514.

[11] Parder, M.L., Tammeleht, A., Juurik, M., Paaver, T., Velbaum, K. and Harro-Loit, H., 2024. Digital Discussion Game on Values: Development, Use and Possibilities for Measuring Its Functionality. In: Y.P. Cheng, M. Pedaste, E. Bardone and Y.M. Huang, eds. *Innovative Technologies and Learning*. Cham: Springer Nature Switzerland, *Lecture Notes in Computer Science*, vol. 14785, pp.193–202. Available from: https://doi.org/10.1007/978-3-031-65881-5_21.

[12] Pavarini, G., McMillan, R., Robinson, A. and Singh, I., 2021. Design Bioethics: A Theoretical Framework and Argument for Innovation in Bioethics Research. *American Journal of Bioethics*, 21(6), pp.37–50. Available from: https://doi.org/10.1080/15265161.2020.1863508.

[13] Serrano, D.R., Dea-Ayuela, M.A., Gonzalez-Burgos, E., Serrano-Gil, A. and Lalatsa, A., 2019. Technology-enhanced learning in higher education: How to

enhance student engagement through blended learning. *European Journal of Education*, 54(2), pp.273–286. Available from: https://doi.org/10.1111/ejed.12330.

[14] Siddiq, F. and Murchan, D., 2024. Towards a code of ethics for using technology-enabled data and related analytic approaches in educational assessment. *Assessment in Education: Principles, Policy & Practice*, 31(5-6), pp.376–400. Available from: https://doi.org/10.1080/0969594X.2025.2453138.

[15] Sleigh, J., Hubbs, S., Blasimme, A. and Vayena, E., 2024. Can digital tools foster ethical deliberation? *Humanities and Social Sciences Communications*, 11(1), p.117. Available from: https://doi.org/10.1057/s41599-024-02629-x.

[16] Van Rooy, W.S., 2012. Using information and communication technology (ICT) to the maximum: Learning and teaching biology with limited digital technologies. *Research in Science and Technological Education*, 30(1), pp.65–80. Available from: https://doi.org/10.1080/02635143.2011.653877.