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Designing with Intelligence. A gracious approach to AI-powered biodigital fabrication

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Abstract

This paper examines the integration of artificial intelligence (AI) into biodigital fabrication, highlighting its potential to revolutionize material innovation through both creative and reflective functions. As a creative partner, AI enhances biodigital design by enabling generative algorithms, advanced simulations, and sensor-driven systems that cocreate with natural processes – optimizing material performance, reducing waste, and accelerating innovation across fields such as architecture, fashion, food and biomedicine. As a reflective tool, AI supports interdisciplinary coherence and ethical accountability by analyzing semantic patterns, mapping knowledge networks, and modelling long-term ecological and societal impacts. These capabilities allow AI to illuminate the flow of ideas across disciplines and support ongoing alignment with ethical and ecological values. Yet, alongside its promise, AI presents risks including the erosion of human agency, amplification of systemic biases, and increasing fragmentation across sectors. To address these issues, this paper proposes the GRACE framework – Goal, Function, Resonance, Agency, Collaboration and Embodiment – as a guide for responsible and sustainable integration of AI in biodigital fabrication. The framework emphasizes aligning AI applications with regenerative, equitable and ecological principles. The paper aims to promote ethical and interdisciplinary AI-driven innovation that reimagines our relationship with materials and living systems by advancing these insights. Future research should focus on operationalizing this framework and developing AI tools that uphold these values throughout the entire lifecycle of design and fabrication.

Keywords

biodigital fabrication; artificial intelligence; material innovation; ethics; graciousness

Diseñar con inteligencia. Un enfoque elegante para la fabricación biodigital con IA

Resumen

*Este documento examina la integración de la inteligencia artificial (IA) en la fabricación biodigital, destacando su potencial para revolucionar la innovación de materiales a través de funciones creativas y reflexivas. Como socio creativo, la IA mejora el diseño biodigital al permitir algoritmos generativos, simulaciones avanzadas y sistemas impulsados por sensores que cocrean con procesos naturales, optimizando el rendimiento del material, reduciendo los residuos y acelerando la innovación en campos como la arquitectura, la moda, la alimentación y la biomedicina. Como herramienta reflexiva, la IA apoya la coherencia interdisciplinaria y la responsabilidad ética a través del análisis de patrones semánticos, mapeando redes de conocimiento y modelando impactos ecológicos y sociales a largo plazo. Estas capacidades permiten que la IA ilumine el flujo de ideas en todas las disciplinas y respalde la alineación continua con los valores éticos y ecológicos. Sin embargo, junto con su promesa, la IA presenta riesgos que incluyen la erosión de la agencia humana, la amplificación de los sesgos sistémicos y el aumento de la fragmentación en todos los sectores. Para abordar estos problemas, este documento propone el marco GRACE (*Goal, Function, Resonance, Agency, Collaboration and Embodiment*; Objetivo, Función, Resonancia, Agencia, Colaboración y Materialización), como guía para la integración responsable y sostenible de la IA en la fabricación biodigital. El marco hace hincapié en la alineación de las aplicaciones de IA con principios regenerativos, equitativos y ecológicos. El artículo tiene como objetivo promover la innovación ética e interdisciplinaria impulsada por la IA que reimagina nuestra relación con los materiales y los sistemas vivos mediante el avance de estos conocimientos. La investigación futura debe centrarse en la puesta en funcionamiento de este marco y el desarrollo de herramientas de IA que mantengan estos valores a lo largo de todo el ciclo de vida del diseño y la fabricación.*

Palabras clave

fabricación biodigital; inteligencia artificial; innovación de materiales; ética;

Introduction: from convergence to intervention

The convergence of artificial intelligence (AI) and biodigital fabrication marks a paradigm shift in our engagement with the material world, with implications far beyond traditional disciplinary boundaries. As researchers within this evolving discourse, we acknowledge the transformative potential and ethical risks of this intersection. Biodigital fabrication – positioned at the crossroads of biology, technology and design – has grown increasingly interdisciplinary, requiring collaboration among scientists, technologists, designers, artists and industry partners to address urgent societal challenges such as sustainability, material innovation and resource equity. AI acts as a powerful catalyst in this movement, functioning both as a creative force – simulating natural systems, modelling complex processes, and generating novel solutions – and as a reflective tool for assessing the impact of interdisciplinary work and ethical parameters. As a creative force, AI enables biodigital processes through generative algorithms, advanced simulations, and sensor-driven feedback systems, enhancing the capacity to develop sustainable, scalable solutions across architecture, food, fashion and medicine. As a reflective force, AI facilitates semantic analysis of interdisciplinary discourse, maps collaborative networks, and analyses multimodal data to reveal how ideas circulate between domains and how these interactions respond to societal and ecological imperatives. Crucially, AI also supports ongoing assessment of the ethical principles embedded in design processes, helping to ensure alignment with intentional ethical frameworks. Nevertheless, the transformative potential of AI also introduces inherent risks. Over-reliance on algorithmic decision-making can erode human oversight and intuition, potentially amplifying existing biases or causing unintended errors. AI-driven optimization may prioritize efficiency and cost-effectiveness at the expense of ecological integrity or biological diversity, with possible consequences such as environmental degradation and disruption of living systems. Without clear ethical guidelines, AI may inadvertently promote extractive practices – reducing complex ecological relationships to simplified computational models and undermining the regenerative potential of biodigital fabrication. Moreover, as individual disciplines independently develop and implement AI technologies without shared objectives or integrative frameworks, the risk of fragmentation increases – producing silos, duplicated efforts and methodological inconsistencies. Simultaneously, unequal access to advanced technologies could deepen social inequalities, undermining goals for inclusive and equitable innovation. Furthermore, the environmental impacts of large-scale AI raise specific concerns for biodigital fabrication. Training and running advanced models require massive amounts of electricity and water, resulting in significant CO_2 emissions and competition with local ecosystems for limited resources. These effects add to the very sustainability challenges that biodigital fabrication aims to address. Recent estimates indicate that data centres worldwide could more than double their electricity consumption to nearly 945 TWh by 2030 – an amount comparable to Japan's entire national usage – with water withdrawals expected to surpass 1 trillion litres annually, mainly driven by AI workloads (IEA 2025a). Peer-reviewed studies also estimate that training a single GPT-scale model can consume over 700,000 litres of fresh water (Zhang *et al.* 2023). Such demands threaten to undermine the ecological integrity of biodigital fabrication if AI is applied uncritically, especially in regions where infrastructure is already fragile or unequal. This "AI divide" – shaped by costs, energy needs and cooling requirements – risks excluding many communities from AI-driven innovation (World Economic Forum 2023). If unchecked, the pursuit of AI-optimized biodigital processes could reinforce extractive practices under a green guise, damaging both ecological balance and social inclusion. To ensure that AI and biodigital fabrication converge in an innovative and gracious manner — in an interdisciplinary, ethically driven, ecologically sensitive way and committed to co-creation with nature – we call for the urgent development of ethical frameworks. This paper aims to foster such a perspective by proposing a framework for considerate biodigital fabrication with AI, designed to reduce risks and promote responsible deployment. Drawing on cutting-edge research and pioneering projects that exemplify ethically conscious innovation, we also highlight areas where future research and development are necessary to embed these principles into practical applications across industries. By transforming these insights into a structured framework, we aim to encourage interdisciplinary dialogue and suggest actionable pathways for AI-enabled innovation that respect the interdependence of life, materials and intelligence.

1. From biological growth to computational form: foundations of biodigital fabrication

Biodigital fabrication represents a groundbreaking convergence of biological processes and digital technologies, offering a novel paradigm for material innovation and production (Arena *et al.* 2021). This interdisciplinary field leverages the principles of regenerative engineering, advanced materials science and digital manufacturing to create materials and structures with unprecedented functionality and sustainability (Matai *et al.* 2020).

From a design perspective, biodigital fabrication represents a new paradigm driven by advances in the omics sciences, enhancing our understanding of biological growth and uncovering an informational matrix at the core of all living things. These scientific insights have led design to expand the biological reference to include nature's processes for ecologically shaping the material world (Estévez & Navarro 2017). In particular, biodigital fabrication creates an interdisciplinary space where computational thinking intersects with biological issues (Lockton & Ranner 2017). Here, digital, network, and advanced manufacturing technologies combine with the transformative properties of biological matter to transfer the generative and performative qualities of the living world into artificial creations. These innovations enable designers to control the structural organization of materials, transforming digital information into tangible physical outcomes while incorporating biological properties into the design process. As a result, new conceptual frameworks are rooted in design practices: unlike traditional approaches that treat biological or living materials as mere building blocks, biodigital fabrication ensures that design and fabrication processes align with natural growth and information processes (Rotondi 2023). This approach generates complex structures that mimic the intelligence, specificity, and active qualities of naturally-developed entities. The typical hierarchical sequence of form, structure, and material is often reversed, with material informing the structure and the structure, in turn, informing the form (Oxman 2011).

Central to biodigital fabrication is, for example, the process of natural and digital morphogenesis. By leveraging algorithms and generative design, biodigital fabrication incorporates mathematical patterns from nature, enabling the creation of complex forms and materials that are structurally efficient and ecologically responsive. This approach challenges traditional views on materiality, integrating dynamic, self-regulating materials that contribute to sustainability, such as bio-fabricated living walls or adaptive facades. This is the case of the bioreceptive living walls developed by Professor Marcos Cruz and his team at the Bartlett School of Architecture: they combine large-scale 3D printing of concrete walls with living organisms (such as moss, algae and fungi) to choreograph their growth into functional patterns. Sometimes, they have combined bio and digital processes into large-scale bioprinting through custom-printed immobilization of microalgae (Malik *et al.* 2019). The concept of large-scale bioprinting has also been explored by Officina Corpuscoli and Co-de-it in the "Bio-ex-machina" project (2016), which involves printing with a customized robotic arm a mixture based on organic waste and mycelium spores to create new morphologically complex types of furniture, with structural and aesthetic qualities shaped by algorithms, robotic behaviours, and the biological growth of the mycelium. These morphogenetic principles extend to structuring new biomaterials and managing their chemical and informational aspects, thereby producing innovative materialities and technological platforms that mimic nature's adaptive intelligence. For example, Neri Oxman and The Mediated Matter Group at MIT have developed a "Water-Based Digital Fabrication Platform" that transforms abundant biopolymers (cellulose, chitosan, pectin) into high-performance, sustainable materials that are printable once mixed with water (Mogas-Soldevila & Oxman 2015). They analysed multi-scale mechanical properties and degradation rates of different biopolymers and employed computational patterns and structures to control these properties, such as transparency, strength and decomposition modalities. The final result is entirely 3D-printed new biomaterials with customized aesthetics and degradation rate modalities.

Designers' skill in managing biological processes through computational platforms has led the discipline to integrate into multidisciplinary groups beyond the typical boundaries of manufacturing and architecture. For example, in the "Tissue Printing" project, the design duo Nervous System actively collaborates in a tissue engineering project with Jordan Miller's bioengineering lab at Rice University to develop software capable of generating multi-vascular networks and custom respiratory pathways for the maintenance of synthetic organs (Antonelli & Tannir 2019). Designers experiment with biodigital approaches to find new ways to manage complex phenomena and propose innovative nature-driven solutions for healthcare, agriculture and food systems, urban planning or social innovation. For instance, EcologicStudio in the "GAN-Physarum" project (2022) leverages the ability of slime moulds to establish more efficient networks to develop an Artificial Intelligence (AI) algorithm capable of informing urban planning based on sustainability principles and optimization of blue-green networks (waterways, planting and parks). In other words, the technological potentials of the biodigital create new cyber ecologies where technology itself mediates between different disciplines, media (physical, digital, biological, cultural), entities (human, natural, artificial), and dimensions of reality (atoms, bits, genes, perceivers), also encouraging collaborative realities. Designer Dorotea Dolinšěk, in the "Ex.A.R.U." project exhibited at the Ars Electronica Center (2024), aims to show this underlying interdependence by combining biological elements (plants), digital elements (a glass sphere with controlled climatic conditions), and human elements (visitors who must contribute to the sustenance of the plants by breathing into the sphere, thus providing the plants with the carbon dioxide they need to live).

2. AI as a dual force in biodigital fabrication

Artificial intelligence (AI) involves developing computer systems capable of performing tasks that typically require human intelligence, such as learning, reasoning, problem-solving, and decision-making. AI systems excel at analysing large amounts of data, identifying patterns, and making predictions, often outpacing human abilities in speed and accuracy (Russell & Norvig 2021). AI is not a single technology but a collection of techniques and technologies with diverse applications, including machine learning, deep learning, and natural language processing. Integrating AI into biodigital fabrication enhances its potential, offering new ways to improve design and production processes. AI tools enable rapid prototyping, optimization, and fine-tuning of designs through simulation and analysis (Gong *et al.* 2023), increasing the precision and efficiency of biodigital fabrication. Additionally, AI's capacity to process large datasets allows for more accurate prediction and modelling of biological processes, leading to unprecedented precision in creating materials with improved properties, as exemplified by the Materials Project (Jain *et al.* 2013). By combining biological and digital design principles, AI helps ensure biodigital fabrication meets functional, ecological, and ethical standards, fostering a more sustainable and responsible approach to material innovation. We focus on three key types of AI: generative AI, which creates new content from data; predictive AI, which assists researchers in making informed decisions through analyses and simulations; and descriptive AI, which examines large datasets to generate clear, accessible insights. These AI types offer numerous possibilities for biodigital fabrication, promoting co-creation with nature, reducing errors, encouraging multidisciplinary approaches, and supporting ethical, responsible design that respects living systems.

2.1. AI as a creative force: helping designers to co-create with nature

There are notable initiatives demonstrating how AI functions as a creative force in biodigital fabrication. EcoLogicStudio's "Deep Green" projects, for instance, employ AI-driven processes to promote regenerative urban ecosystems through biodigitally fabricated algae and mycelium structures, effectively translating ecological challenges into innovative design solutions (Pasquero & Poletto 2023). These projects are made possible by AI tools specifically designed for biodigital fabrication and by more general tools such as MidJourney, which assist designers in conceptually exploring and quickly visualizing bioinspired patterns and forms via textual prompts. AI-powered simulation tools aid designers by accurately predicting physical and biological properties. For example, in her project "BioAI-Formed Mycelium" (2023), Amy Karle explores how AI can assist in designing and cultivating biomaterials, improving their functionality and sustainability. She employs biomimetic design, inspired by coral forms, to develop structures capable of capturing and utilizing carbon to mitigate carbon emissions from industrial sources and decontaminate highly polluted areas. Additionally, the AI-supported simulation approach diminishes the need for extensive experimental trials, streamlining optimization processes in tissue engineering and biofabrication applications. For instance, DAN*NA company uses AI materials design software to generate virtual clones of target materials, allowing developers to forecast novel formulation properties without lengthy experimental procedures. Similarly, researchers at the Tokyo Institute of Technology have applied machine learning with artificial neural networks to predict water-repelling characteristics and protein adsorption in self-assembled monolayers, supporting advanced material screening and design (Kwaria *et al*. 2020).

These AI-driven methods also accelerate innovation and enhance efficiency in generating and creating biomaterials. This is the case with molecular design software powered by artificial neural networks and generative adversarial networks (GANs), which assist in predicting and creating new molecular structures with precise biological functions, such as advanced biocompatibility or environmental responsiveness. These algorithms can produce new biomaterials, tissues, and organ designs based on specific criteria and customizations. They can also generate synthetic data to train other AI models, increasing prediction accuracy and supporting the design process more effectively than ever before (Xue *et al*. 2021).

2.2. AI as a reflective force: fostering interdisciplinarity and ethical decision-making

AI tools in biodigital fabrication serve not only as creative instruments but also as reflective mechanisms, allowing designers and researchers to highlight how ideas flow across disciplines and how these interactions address societal and ecological challenges. They also track and assess the embodiment of ethical principles throughout the creative process, guaranteeing ongoing alignment with the ethical frameworks they aim to uphold and tackling potential moral concerns.

2.2.1. AI in ethical decision-making

AI's capacity to model ethical outcomes and predict future scenarios provides valuable insights for biodigital fabrication. Tools such as ethical forecasting and scenario-modelling systems enable designers to assess the long-term societal and ecological impacts of their work. For instance, Delphi – an AI system developed at the University of Washington and the Allen Institute for Artificial Intelligence – predicts human moral judgments by drawing on large datasets of crowdsourced ethical opinions (Jiang *et al*. 2025). Although not specifically created for biodigital fabrication, it exemplifies how specialized ethics agents might one day assist designers in anticipating stakeholder perspectives on the moral implications of their choices. Besides forecasting, AI can aid the development of customized ethical evaluation frameworks. Checklist generators could, for example, tailor considerations to the parameters of a given project, from environmental impact and social equity to alignment with sustainability goals. Machine learning models trained on bioethics and design ethics case studies could offer real-time insights into emerging dilemmas, guiding designers through complex decisions. To establish trust, however, such tools must be trained on diverse, high-quality datasets, be subject to ongoing audits, and maintain transparency and explainability, with clear performance standards and risk-management measures (Saxena 2024).

2.2.2. AI in measuring the impact of interdisciplinarity

AI-powered semantic analysis tools, such as transformer-based models like BERT (Bidirectional Encoder Representations from Transformers), enable the identification of implicit connections between interdisciplinary research, revealing opportunities for integration and areas needing further ethical alignment (Acheampong *et al*. 2021). These tools analyse large volumes of interdisciplinary data, uncovering nuanced semantic patterns that link seemingly unrelated fields. For example, these AI methods could map connections between biofabrication research, sustainability practices, and social justice initiatives, identifying areas where ecological and social concerns intersect and informing the ethical decision-making process. Here, it is vital to recognize that impactful research depends less on the overall interdisciplinary nature of author teams and more on the diversity of knowledge they harness (Abbonato *et al*. 2024). Another example of AI's role in fostering interdisciplinary collaboration is AI-driven knowledge graph approaches, such as SciSight (Hope *et al*. 2020). This reflective visualization capability helps researchers intuitively understand interdisciplinary connections, prompting deliberate ethical and methodological considerations.

3. Towards a gracious approach to biodigital fabrication with AI

The previous chapters have demonstrated how AI transforms biodigital fabrication as a creative and reflective force. From generative design of biomaterials to interdisciplinary mapping and ethical forecasting, AI offers immense potential to accelerate regenerative and sustainable innovations. However, as we have also outlined, these transformative capabilities carry significant risks: ecological oversimplification, human bias, social inequality, energy consumption, and fragmented implementation across disciplines and sectors. AI-driven biodigital fabrication faces notable process and system-level challenges, including the need for large amounts of high-quality biological data, specialized computational infrastructure with high-performance GPUs and storage systems, and substantial costs that particularly hinder adoption in regions with limited technological access (Ramesh *et al*. 2024). These requirements create barriers where basic infrastructure such as reliable electricity and high-speed internet remain inaccessible, effectively excluding many developing regions from engaging in AI-enhanced biodigital innovation (Singh *et al*. 2020). Furthermore, without deliberate alignment, AI could inadvertently reproduce extractive logics or reinforce disciplinary silos. We need a coherent ethical framework that ensures AI integration into biodigital fabrication is driven not only by efficiency, aesthetics, or novelty but also by purpose, responsibility, and ecological resonance. We advocate for a considerate approach to biodigital fabrication with AI, embodied by the GRACE framework – an acronym for Goal function, Resonance, Agency, Collaboration and embodiment (Buik, 2024). Applying this framework to

AI in biodigital fabrication provides a practical structure for embedding ethical values into practice.

Figure 1. The GRACE framework applied to biodigital fabrication

3.1. Goal function: aligning AI to regenerative principles in defining purpose and impact

At the core of a gracious approach is the intentional articulation of purpose. In biodigital fabrication, this involves setting design and technological goals that extend beyond performance or aesthetics towards regenerative and equitable outcomes that promote human and ecological well-being. As previously discussed, AI's creative capabilities – mainly through generative algorithms and predictive modelling – provide unprecedented opportunities to optimize resource efficiency, reduce waste, and design for long-term ecological sustainability. In architecture, for example, AI-enhanced optimization tools can simulate material behaviour and lifecycle impacts, enabling early design decisions that reduce embodied carbon and resource footprints. AI models improve irrigation systems and nutrient flows in agriculture to support soil health and water conservation, directly advancing regenerative farming practices (Kumar *et al.* 2023). Crucially, goal function also addresses the social dimensions of biodigital fabrication. AI can assist in reducing inequalities by enabling more affordable, localized, and adaptable design solutions. For instance, by modelling context-specific needs and constraints, AI can support healthcare applications in underserved regions (Perez *et al.* 2025) or aid smallholder farmers in adapting to climate variability (Leal Filho & Gbaguidi 2024). Embedding these ethical priorities from the outset transforms AI from a mere efficiency tool into a co-creative partner for change. In this manner, clearly defined and value-aligned goal functions ensure that the creative potential of AI in biodigital fabrication is continuously guided by an ethical compass – one that is sensitive to the interdependence of materials, systems, designers and life itself.

Applying this principle to EcoLogicStudio's "Deep Green" project leads to the following analysis. As said, this project uses AI-driven processes to fabricate algae and mycelium structures for regenerative urban ecosystems (Pasquero & Poletto, 2023). AI here helps translate ecological goals (e.g., carbon absorption and waste reduction) into architectural form. While sustainability is central, efficiency in growth and optimization might overshadow broader social equity considerations (e.g., accessibility of such infrastructures in non-urban or underserved contexts). Explicitly embedding goal functions around inclusivity and affordability (not only ecological regeneration) could strengthen its impact. For instance, AI models could simulate how algae-integrated facades would perform in low-resource contexts, guiding scalable designs beyond elite architectural projects.

3.2. Resonance: responding to ecological and social contexts

Resonance demands a design logic that listens – to ecosystems, communities, materials, and life models. This principle insists that biodigital fabrication must recognize natural systems and align itself with the social and cultural contexts in which technologies are embedded. When applied resonantly, AI becomes a translator of intelligence – mediating between the language of life, human values, and design logic. Instead of treating sustainability as an afterthought, resonance repositions nature as a co-creator of design. Simultaneously, AI tools can reveal social dynamics – by analysing cultural narratives, stakeholder perspectives, or community needs – ensuring fabrication processes respond not only to ecological rhythms but also to human priorities of equity, justice and inclusivity. Significantly, resonance goes beyond biomimicry. It is not just about copying natural forms but about co-evolving with living systems and human societies – recognizing their agency, variability and feedback capacity. In this spirit, AI tools analysing large datasets – from protein structures and soil microbiomes to social media discourse and participatory design feedback – can uncover subtle design principles encoded in both nature's 3.7 billion years of experimentation and humanity's evolving cultural practices. By aligning with the intelligence of both ecosystems and communities, resonance redefines innovation as an act of attunement.

Applying this principle to Karle's "BioAI-Formed Mycelium" leads to the following analysis. Karle uses AI simulations to biomimetically design coral-inspired mycelium structures that capture carbon and enhance sustainability. The ecological resonance is evident: AI mediates between natural intelligence (coral forms) and the design outcomes. However, this connection could be strengthened by moving beyond biomimicry to include both ecological variability and social dimensions. Current AI might still prioritize form-function optimization without fully considering how materials interact with dynamic ecosystems (e.g., soil microbiomes or climate stressors) or how they are perceived within specific cultural and community settings. By coupling AI simulations with ecological datasets from living environments and integrating insights into community needs, cultural practices, and social equity, projects like "BioAI-Formed Mycelium" could move from aesthetic analogy towards holistic reciprocity – co-evolving with both natural systems and human societies.

3.3. Agency: empowering stakeholders and living systems through ethical transparency and empowered decision-making

Agency refers to the capacity of both human and more-than-human actors to meaningfully influence biodigital futures. It opposes the automation of ethics and the outsourcing of responsibility to computational logic. Instead, it advocates for human discernment, contextual judgment, and the ability to choose wisely – especially in complex, entangled, high-stakes design processes. In AI-powered biodigital fabrication, agency is strengthened when tools are designed not to dictate actions but to support creative and reflective decision-making. This includes AI systems that reveal potential trade-offs, simulate long-term ecological effects, or visualize ethical consequences of design interventions. For instance, AI-powered bioreactor monitoring systems can assist practitioners in making nuanced, real-time decisions to improve the well-being of living materials – without reducing them to mere inputs. Likewise, ethical scenario-modelling platforms can enable designers to anticipate and navigate dilemmas before they manifest physically. Crucially, agency must be distributed. It is the designer's prerogative and must be extended across teams, stakeholders, and even the biological systems themselves. This implies creating participatory design ecosystems where farmers, patients, ecologists – or even proxies for the non-human – can inform what is a desirable outcome. AI's role here is to scaffold this collective agency by making complex information understandable, identifying blind spots, and emphasising long-term implications. When AI is designed to serve – not replace – agency, it becomes a reflective partner in ethical inquiry, fostering biodigital fabrication processes that are both intelligent and intentional.

Applying this principle to DAN*NA's AI Materials Design Software leads to the following analysis. DAN*NA employs AI to create virtual clones of materials, predicting their properties before physical prototyping. This enhances human agency by giving designers decision-making power based on simulations. However, agency is constrained if the AI's predictive logic remains a "black box". Designers may rely on opaque outputs without fully understanding the underlying assumptions. To strengthen *agency*, the software could incorporate explainable AI features – demonstrating how predictions are made and providing scenario comparisons. This would enable designers to make ethically thoughtful decisions rather than defaulting to algorithmic authority. Moreover, agency could be expanded by including proxies for non-human actors – such as ecological thresholds or organismal stress indicators – ensuring that nature itself is represented as an active participant in decision-making.

3.4. Collaboration: bridging disciplines, systems and species

Collaboration is not merely a matter of assembling expertise – it is about cultivating shared language, mutual intelligibility, and the ethical scaffolding for co-creation across disciplines, cultures and species. In the context of biodigital fabrication, AI becomes a potent mediator of this complexity, supporting the emergence of cohesive, interdisciplinary innovation ecosystems. AI's reflective capabilities are pivotal in strengthening collaboration by revealing latent thematic overlaps, methodological complementarities, and conceptual bridges between traditionally siloed fields such as biology, architecture, computer science and materials science. Semantic analysis tools and AI-powered knowledge graphing systems (like the previously mentioned SciSight (Hope *et al.* 2020) make visible the otherwise opaque connections that weave through research domains, enabling designers and scientists to identify shared inquiries and complementary approaches. More than mapping existing structures, AI also fosters *emergent* collaboration. Predictive models like those discussed by Gao *et al.* (2024) can identify where interdisciplinary impact is likely to occur based on evolving patterns in patent citations. These insights allow institutions and researchers to build bridges – rather than proactively repair fragmentation. AI also facilitates collaboration on a pragmatic level. Translation tools and intelligent search engines help overcome linguistic and disciplinary barriers, democratizing access to knowledge and allowing diverse stakeholders to engage meaningfully in collective problem-solving (Steigerwald *et al.* 2022). Beyond academia, AI-powered analyses of social media discourse (Saragih & Manurung 2024) provide dynamic insights into public sentiment, commercial trends, and policy relevance – key elements for scaling collaborative impact. Importantly, collaboration in a gracious paradigm extends beyond the human. As AI enables us to interpret and model living systems with greater sensitivity – such as decoding the combinatorial structure of sperm whale vocalizations (Sharma *et al.* 2024) – it opens space for considering ecological actors not as resources but as participants. This shift is exemplified by emerging tools for interspecies communication, marking a move towards more-than-human collaboration grounded in mutual understanding. In this light, collaboration becomes interdisciplinary and interspecies – an ethic of working *with* rather than *on* the living world. By facilitating clarity, equity, and resonance across domains, AI becomes more than a connector of disciplines – it becomes a steward of gracious collaboration.

Applying this principle to Tokyo Institute of Technology's ANN for Protein Adsorption project leads to the following analysis. Researchers applied artificial neural networks to predict protein adsorption on self-assembled monolayers (Kwaria *et al.*, 2020). This exemplifies collaboration across biology, computer science and materials design. However, while technically interdisciplinary, the collaboration is limited to narrow research goals; ethical and ecological dimensions of biodigital fabrication remain peripheral. Embedding *collaboration* more broadly could mean linking this AI tool to sustainability frameworks (e.g., predicting adsorption effects relevant for biodegradable materials or biomedical ethics). Such integration would widen the collaborative impact beyond disciplinary silos.

3.5. Embodiment: making data felt and impact measurable, promoting ethical and ecological integration

Embodiment, the final pillar of the GRACE framework, reminds us that ethics must not remain abstract. They must be enacted – materialized through design decisions, manifested in production systems, and felt in the lived experience of ecosystems, communities and organisms. In biodigital fabrication, embodiment asks: How do our values appear in matter, methods, and multispecies relations? With its capacity to monitor, measure, and model in real-time, AI offers designers a reflective feedback loop that anchors ethical intentions into tangible outcomes. Advanced sensing technologies enable continuous tracking of environmental conditions, resource flows, and organismal well-being across biofabrication systems. These data streams facilitate ongoing alignment with ecological thresholds and social commitments when incorporated into responsive design platforms. In this way, ethics become embedded not only in the blueprint but also in the system's behaviour. Importantly, embodiment is not just technical; it is also epistemological. It calls for a shift from designing about life to designing with life. AI can support this transition by simulating material outcomes and relational ones – how a material ages, decomposes, nourishes, or interferes with its surroundings. These predictive capacities allow designers to anticipate consequences across time and space, weaving ethics into the very material logic of their practice. Therefore, embodiment within AI-powered biodigital fabrication is not merely about incorporating environmental data or satisfying compliance checklists. It is about choreographing systems in which ethics are lived – through every algorithm, interface, molecule, and gesture.

Applying this principle to EcologicStudio's "GAN-Physarum" project leads to the following analysis. This project combines slime mould behaviour with AI algorithms to support sustainable urban planning. It embodies AI-ecology interaction by translating living intelligence (Physarum's network efficiency) into design logic. However, embodiment here risks remaining symbolic: slime mould intelligence is abstracted into data, potentially stripping away the ecological context of the organism. Strengthening embodiment would involve reintegrating ethical monitoring – e.g., AI systems that model not only Physarum-inspired networks but also ecological side effects of deploying such networks in urban settings. This grounds the "embodied" use of life's intelligence in both material and ecological responsibility.

Conclusion

This paper explored the transformative intersection of artificial intelligence and biodigital fabrication, positioning AI as a creative and reflective force in shaping regenerative, interdisciplinary and ethically grounded material futures. We examined its dual role: supporting design innovation through generative and simulation tools, and enabling ethical and interdisciplinary reflection through semantic analysis, collaboration mapping and scenario modelling.

Our inquiry was structured around four key goals: advancing regenerative biodigital fabrication with AI as a partner; enhancing interdisciplinary collaboration across design, biology, computation and materials science; addressing urgent societal and ecological challenges; and establishing an ethical framework for AI integration that centred on both human and more-than-human agency. We demonstrated the field's growing ecological alignment and innovation capacity by reviewing current AI applications in biodigital fabrication. However, we also underscored the risks of fragmented implementation, extractive design logic and the absence of shared ethical foundations. To address these risks and guide future development, we proposed the GRACE framework: a five-pillar model encompassing goal function, resonance, agency, collaboration and embodiment. GRACE offered a structured approach to embedding ethical, ecological, and interdisciplinary considerations into AI's design, development and deployment in biodigital fabrication. It also responded directly to the societal urgency of this gracious approach, driven by the increasing need for regenerative solutions, the growing demand for sustainable practices, and the ethical imperative to ensure that technology benefits all of humanity and the environment. This research suggested that when AI is framed not merely as a tool for optimization but as a co-creative and reflective partner, it could support the emergence of a more gracious design paradigm – responsive to complex ecological systems, socially inclusive, and ethically intentional. Future research should focus on further operationalizing the GRACE framework and developing domain-specific tools and metrics that translate these principles into practice. Interdisciplinary prototyping environments, AI-assisted ethics assessment platforms, and participatory design methodologies with multi-stakeholder inputs represent promising directions for embedding graciousness into the technological and material realities we are now shaping. In doing so, biodigital fabrication may not only innovate materials, but reimagine our relationship with them – and with ourselves.

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