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Multispecies reconciliation principles in biodesign practice

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Abstract

Biodesign is an emerging field that brings together a wide range of practices, connecting fundamental research, applied sciences and creative approaches. Within this spectrum, a tension exists between instrumental uses of biological processes and a growing sensibility that acknowledges the agency of living materials and organisms. This study proposes reconciliation as a guiding concept for biodesign, understood not as a metaphorical gesture but as a concrete and plural perspective that promotes species coexistence and conservation. We contextualise reconciliation through restoration, reciprocity and relationality as distinctive yet interconnected design and ecological principles that extend beyond normative human exchange, promoting multispecies coexistence. Through a mix of reflexive thematic synthesis and the analysis of selected case studies derived from the authors' own projects, employed as a practice-based methodological inquiry and primary source of empirical and reflective insight, we explore how reconciliation is enacted and experienced in practice. Finally, we propose a conceptual framework to address reconciliation in biodesign, offering guiding concepts and key questions to discuss and support ecological flourishing in multispecies collaborations.

Impact statement

This study arises from the authors' shared aspiration that biodesign should support species coexistence and cohabitation. Building on the diversity of the authors' academic backgrounds and reflecting biodesign's hybrid nature and wide range of approaches, we share the view that designing with biology necessitates a conscious practice that considers reconciliation with nonhumans. We advocate for making this a foundational principle for biodesign. We argue that the transformative impact of biodesign depends on considering reconciliation as the negotiated alignment of human and non-human systems, grounded in the three core principles of restoration, reciprocity and relationality, rooted in multispecies interconnectedness.

In this work, we integrate our views to provide a framework for discussing reconciliation across a plurality of disciplines, aiming to encourage long-term ecological thinking over short-term gains. Ultimately, this study can support local and global initiatives to foster multispecies coexistence in cities and rural areas across eco-social and technological gradients, enhancing reconciling practices to engage with biology from multiple perspectives.

Introduction

As human activities increasingly create low-biodiversity built environments and fragmented habitats, there is a growing and urgent need for innovative approaches to integrate species diversity and promote conservation. Contemporary practices engaging with living systems encompass a range of disciplines, in which an increased sensitivity towards multispecies worlds is recognised as a central epistemic and ethical lens rather than a peripheral concern (Irwin *et al.* 2020; McGuirk, 2025; Tsing *et al.* 2017). This shift is driven by the recognition that human-managed environments are now decisive sites for biodiversity loss and ecological transformation, and that design interventions can either exacerbate or remediate these dynamics. As a result, we are witnessing the emergence of concepts that incorporate a plurality of agents, regenerative processes and systemic approaches, reframing humans as part of a bigger whole. Concepts such as regenerative design (Mang *et al.* 2016), urban ecology (Niemelä *et al.* 2011), reconciliation ecology (Rosenzweig 2003), nature-based solutions (Seddon *et al.* 2020), bio-receptive design (Cruz and Beckett 2016; Pollini and Rognoli, 2021), probiotic architecture (Beckett 2024), biohybrid architecture (Ayres 2021) and nature-centred design (Paoliello 2025) emerge as powerful answers for multispecies collaboration and cohabitation.

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Reconciliation is increasingly emerging as a pivotal yet underexamined concept across a range of disciplines concerned with human–nonhuman relations, including ecology, anthropology, indigenous studies and, more recently, biodesign and industrial biotechnologies. Often addressed in contexts of social justice, the concept of reconciliation can be extended to various fields beyond human-centred frameworks to address the repair of disrupted ecological, material and multispecies relationships. In ecology, it shifts the focus from restoring degraded landscapes to fostering coexistence within imperfect shared habitats, asking people to reimagine their relationships with local lands (Guidi 2025; Rosenzweig 2003); in anthropology and Indigenous epistemologies, it foregrounds relational accountability and reciprocal care (de la Cadena 2015; Haraway 2003; Kimmerer 2013); in biodesign, connected concepts begin to surface, foregrounding the role of living materials in fostering ongoing ecological processes through design, supporting mutualism and coevolution (Karana *et al.* 2023).

Despite its growing relevance, reconciliation remains conceptually diffuse and insufficiently theorised within design practice, where its potential to guide more ethical, regenerative and situated modes of innovation has yet to be fully articulated. While concepts related to reconciliation are increasingly recognised as important frameworks for rethinking how living systems are engaged, cultivated and instrumentalised, to our current knowledge, the term "reconciliation" itself has not yet been explicitly described or formally addressed in the design or biodesign literature.

In this study, reconciliation is advanced as a guiding principle for biodesign, understood here as a cross-disciplinary field informed by diverse approaches to engaging and working with biology. Three principles have emerged as the structural anchors of reconciliation through a two-stage inquiry. First, a reflexive thematic analysis (Ahmed *et al.* 2025) of literature across ecology, anthropology, Indigenous epistemologies and biodesign was conducted, in which recurring concepts related to reconciliation were identified across these bodies of knowledge. This analysis consistently surfaced three thematic clusters: the repair of degraded ecological relationships, the generative exchange between human and non-human agents and the ontological entanglement of humans within broader living systems. These were consolidated into the principles of restoration, reciprocity and relationality. In a second phase, the three principles were iteratively applied and refined through a practice-based case study analysis (Eisenhardt 1989; Rowley 2002), which led to the definition of strategies and guiding research questions across varied biodesign contexts. The result of the study is a framework, grounded simultaneously in cross-disciplinary evidence and first-hand practice, that addresses reconciliation as an active effort to work across damaged or conflicting relationships among human needs, technological systems, ecological processes and nonhuman agencies. We use it not as a claim that these tensions can be fully resolved, but as a guiding orientation for design practice: to acknowledge harm and dependency, to negotiate responsibilities and to develop practices that make coexistence more achievable.

Defining reconciliation across plural perspectives

The concept of reconciliation plays a significant role across different fields of knowledge. Global connections can be found in how various disciplines address this notion, defining possibilities for repairing relationships, reconfiguring responsibilities and enabling more just forms of coexistence. In ecology, reconciliation has been defined as the possibility of redesigning anthropogenic habitats to serve a broader array of species, improving conservation while suggesting infrastructures of cohabitation (Miller 2006; Rosenzweig 2003). In anthropology and related fields, multispecies ethnography documents cultures, perspectives and practices in multispecies settings, foregrounding everyday cohabitation with companion and stranger species and challenging human exceptionalism through accounts of becoming-with other-than-human life (Haraway 2003). Indigenous perspectives further deepen reconciliation by articulating practices of interdependencies and responsibility towards land and more-than-human kin, insisting that ecological repair entails renewing reciprocal gift relations rather than solely technical mitigation (de la Cadena 2015; Kimmerer 2013). In biodesign, multispecies (Escobar 2018; Van Dooren *et al.* 2016) and more-than-human (Braidotti 2013; Forlano 2017; Rosén *et al.* 2024; Wakkary 2021) design approaches operationalise reconciliation by reimagining biological materials, processes and environments as sites of interspecies reciprocity and coexistence, rather than unilateral human utility. In industrial biotechnologies, the term reconciliation has been used to describe the transition from a linear economic model to a sustainable circular bioeconomy (D'Amato *et al.* 2017). Through key strategies such as biocatalysis, material substitutions and synthetic biology, the aim is to shrink industrial footprints to allow natural ecosystems to thrive. Resource reconciliation focuses on side-stream strategies (Scarlat *et al.* 2015), biotic reconciliation on cellular agriculture (Treich 2021) and climate reconciliation on the use of carbon (Hepburn *et al.* 2019) as a feedstock (Mahmud *et al.* 2025).

Taken together, these plural perspectives allow reconciliation to be understood not as a metaphorical gesture but as a concrete, operational commitment to designing infrastructures, technologies and interfaces that enable conservation, collaboration and cohabitation across species, guided by the question of what findings and innovations can be mobilised to align scientific insight with situated practices.

Restoration, reciprocity and relationality as principles for reconciliation

Within the expanding discourse of biodesign, emerging concepts are resonating with the transversal principle of reconciliation. In particular, restoration, reciprocity and relationality have emerged as interrelated stances through which designers reorient practice toward ecological coexistence and multispecies flourishing. These concepts were selected not as exhaustive categories, but because they consistently recurred in the reflexive thematic analysis (Ahmed *et al.* 2025) of the literature and in the authors' practices, as complementary modes of engaging with ecological repair, interdependence and multispecies relations in biodesign. A practice-based case study analysis (Eisenhardt 1989; Rowley 2002) sustained the discussions within the authors' group, in which each contributor reflected on the assumptions, tensions and ethical commitments related to the three principles as they appear in their own practice. Across these discussions, the three stances repeatedly appeared as distinct yet interconnected ways of reorienting design practice toward ecological coexistence and multispecies flourishing.

Restoration

Restoration of ecosystems is the practice and study of the intentional rehabilitation of damaged ecosystems. This place-specific, non-universal strategy aims to restore ecological structure, species

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composition and functional processes (SER 2004). In conservation biology, this is commonly associated with "reservation," the practice of protecting large, contiguous sections of land from human intrusion. Reservation stabilises species variety throughout generations, allowing reproduction and evolutionary resilience. Traditional ecological restoration follows a structured project cycle that involves ecological and social actors in multiple stages – assessment of degradation, goal-setting and planning, active intervention, recovery monitoring and ongoing adaptive management – as outlined in the SER International Standards for the Practice of Ecological Restoration (Gann *et al.* 2019; Nelson *et al.* 2024; SER 2004).

The species–area relationship suggests that larger areas support greater diversity and redundancy, with implications on how reserved habitats are sized and connected (MacArthur and Wilson 1967). However, as industrialisation fragments terrestrial ecosystems, such "reserved" regions become insufficient to sustain global biodiversity. Rosenzweig (2003) argues that limiting conservation to "wild" habitats will cause a catastrophic loss in species richness. Recent studies show that temperature and land-cover change synergistically accelerate species decline in fragmented habitats (García Criado *et al.* 2025) while urban and managed landscapes can create novel, low-intensity niches – through exposed substrates, irregular disturbance and relaxed maintenance – that act as complementary refuges for many disturbance-tolerant and specialist species (Lundholm and Richardson, 2010). Acknowledging these new global frameworks, like the EU Nature Restoration Law (2024), highlights that restoration must expand beyond isolated, reserved (also from everyday human life) patches for long-term resilience (Kupilas *et al.* 2024). What Rosenweig (2003) suggested as reconciliation ecology aims to "blend a rich natural world into the world of economic activity," producing species-friendly living, working and playing environments. This win-win theory has been translated into practice via "Biodiversity-Inclusive Urban Planning and Design" (BIPD) research, which encourages cities to participate in the Kunming-Montreal Global Biodiversity Framework (Target 12[1]), and follows frameworks like and Biodiversity Sensitive Urban Design (Garrard *et al.* 2018), and ecological design which is "context-specific ('Place'), restore the local ecology ('Restoration') and encourage people's role as active participants in the ongoing care of the land ('Stewardship')" (Van der Ryn and Cowan 1995; Hernandez-Santin *et al.* 2023). In addition to biological benefits, reconciliation ecology addresses urban psychological divides, where industrialised societies increasingly lose everyday contact with living systems, described as "plant blindness" (Stagg *et al.* 2023) and the "extinction of experience" (Gaston and Soga 2020). These contribute to a self-reinforcing cycle where the loss of such experiences erodes the stewardship necessary for ecological health, ultimately compromising the "One-Health synergy" (FAO, UNEP, WHO and WOAH 2022) that binds human wellness to the vitality of our shared environment, reminding us that when nature thrives, we thrive. Even modest urban "habitat gardens" can reduce "extinction of experience" effects by reconnecting urbanites with local biodiversity and encouraging stewardship (Egerer *et al.* 2023; Soga and Gaston 2016; Southon *et al.* 2024). Habitat gardens, therefore, show how small, situated interventions can support biodiversity while changing how people perceive and care for local ecosystems. Biohybrid design can be understood as an extension of this logic: instead of merely planting or managing habitats, it actively crafts substrates, structures and material conditions that enable organisms to live, grow and interact.

This does not mean replacing established conservation and restoration techniques. While traditional conservation and restoration techniques such as thinning, mowing, burning, invasive species control and commercial insect hotels, measurably support biodiversity trajectories (Lehmann *et al.* 2022), they often operate through a primarily managerial understanding of habitat: reducing pressures, maintaining target conditions, or restoring selected ecological functions. Contemporary biodesign can contribute to this established conservation framework by adding a constructive, material, technological and social design capacity. In its current form, biodesign often begins from the assumption that modern technologies can be used to understand living organisms, mediate their growth and guide biological processes toward particular design objectives. Over the last few years, however, this technological orientation has increasingly been accompanied by ethical reflection, especially around the instrumentalisation of living beings, the responsibilities of care and the social conditions under which biological systems are designed, cultivated and displayed. This shift is also supported by the intrinsically interdisciplinary and increasingly transdisciplinary, character of biodesign practice, where engineering approaches such as bioremediation can be combined with the aesthetic capacities of organisms and with design knowledge about participation, public communication and social integration. Rather than replacing conventional ecological management, biodesign extends what conservation can do by translating ecological knowledge into situated structures, substrates, textures and microclimatic gradients through which more species can inhabit, interact and persist. Across scales, from spatial planning to permaculture principles and material fabrication, it can generate complex forms, varied surfaces and novel biomaterials that help produce the "habitability" necessary for diverse life forms to thrive (Zhou *et al.* 2022). This includes, for example, mineral and lignocellulosic composites that retain moisture, buffer temperature, slow decomposition, or provide graded porosity for nesting, microbial colonisation and multispecies succession (Parker *et al.* 2023). In this sense, biodesign makes a distinctive contribution to conservation by moving from protecting or managing habitats toward actively crafting the material, experiential and social conditions for coexistence.

Building on this adaptive understanding, spatial design operates as a mediating layer between restoration science and material practice. Through the lens of spatial thinking, biodesign configures hybrid zones, or ecotones, where human-built structures meet non-human living systems. These zones utilise textured facades (Cruz and Beckett 2016; Larikova *et al.* 2022), insect refugia (Ilgün and Ayres 2016; Meier *et al.* 2020), bioreceptive artefacts (Keune *et al.* 2025; Pollini *et al.* 2023; Pollini 2026) and found that differentiated surface roughness is not a decorative feature but an ecological affordances that shape colonisation sequences and multispecies interactions. At the landscape scale, this approach layers permaculture-inspired polycultures with engineered living materials that promote soil regeneration and microhabitat diversity. Practices associated with permaculture provide systemic principles such as stacking functions, closed nutrient cycles and long-term soil building. These principles can be combined with biohybrid experiments, such as living structural systems developed by Baubotanik (Dörfler and Hueber 2021), fungal composites used as degradable habitat nurturing substrates (Loop Biotech, n.d.) and research on responsive biohybrid installations by the Living Architecture Systems Group. Such combinations extend permaculture thinking into the domain of engineered living materials, where growth, decay and microbial succession become active

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components of spatial design rather than background processes. Ultimately, this multi-scalar approach recasts users, materials, microbes, fungi, insects, cryptogams and infrastructure as co-participants in a shared ecological landscape. From a reconciliatory point of view, the human-built environment thus transforms from a degraded niche into a dynamic ecotone where communities converge, biodiversity peaks and humans and non-humans co-adapt across scales, from microscopic exchanges to shared social practices.

Reciprocity

Traditionally understood as a normative exchange among humans, reciprocity is grounded in the idea of fair return. In biodesign, ecology and more-than-human perspectives, the concept extends to encompass relationships between humans and non-humans (Askew 2025; Kimmerer 2013), with a focus on ecological rebalancing following histories of extraction. In this context, success is evaluated qualitatively through multispecies flourishing (Groutars *et al.* 2024), biodiversity gains and long-term ecological participation.

Three main ways of understanding reciprocity can be identified: (1) a restricted approach, based on intentional exchange among humans; (2) a systemic approach, grounded in ecological feedback and mutualism without conscious intention and (3) a relational approach, in which humans and non-humans possess agency and participate in co-constitutive relationships (Vaccaro 2025). In compensatory approaches, the notion of "giving back" may reproduce an extractive logic in which reciprocity appears as a subsequent gesture of compensation. Conversely, the relational perspective resonates with Emanuele Coccia's view of life as a continuous metamorphic flow (Coccia 2022), as well as with Indigenous and posthuman ontologies that understand reciprocity as kinship and co-constitution (Braidotti 2013; Descola 2013; Himes *et al.* 2023; Marihuan and Rapimán 2019; Viveiros de Castro 2005). This perspective challenges the conception of nature as a resource (Díaz and Pascual 2025; Mace 2014; Pascual *et al.* 2017) and reorients design toward continuous relationality among species (Escobar *et al.* 2024), paying attention to ecological temporalities and situated care, with shared responsibility. Within this framework, biodesign can be seen as a practice in which different forms of agency hybridise to sustain vital interconnections and coevolutionary processes. Biodesign guided by reciprocity does not operate as an *ex post* corrective response, but as a continuous practice inherent to the relationship itself.

When reciprocity is reformulated beyond normative exchange and understood as a relational and systemic condition of coexistence, ecological systems offer concrete models of how these dynamics are organised and stabilised. In living systems, reciprocity does not depend on moral intention or symbolic return; it emerges through metabolic interdependence, spatial structuring, reproductive coupling and adaptive feedback. This modality presents reciprocity not as an episodic act of compensation, but as an organising principle of multispecies persistence.

Relationality

Relationality is a key concept in indigenous and local cultures, where the world is understood as a web of relationships and responsibilities that connect humans to a bigger system rather than to exploitable resources (Nelson and Shilling 2018; Tynan 2021). In comparison with the previous principles, what characterises relationality is that there are no precise measurements, expectations, demands or preset timeframes, but just the acknowledgement of existing together, which makes relations the perceived reality or, as it has been defined, a *relational reality* (Tynan 2021). Indigenous relational science and knowledge systems (Pérez *et al.* 2025) present an epistemology rooted in interdependence, responsibility and territorial continuity, arising from the ongoing relationships among humans, non-humans, ancestors and territories. Actions within these systems are inherently participatory and are situated within cycles of seasonal synchronisation and long-term stewardship. Ecological phenomena are understood through situated practices such as ceremony, subsistence and kinship, where ethical responsibility is inseparable from empirical observation. Consequently, Indigenous relational science reconceptualises sustainability as an ongoing practice of care, adaptive learning and collective continuity across generations (Ibid.), providing methodological and ontological foundations for ecological design and restoration that extend beyond human-centred frameworks.

If the environmental crises we face are "*less about resource degradation and species extinction than of degradation of our relationship with the living world*" (Kimmerer 2012), then cultivating the awareness of interconnectedness and being together in a given space/time can be seen as a reconciliation practice. In this study, relationality designates more than a methodological orientation or an ethical add-on; it names an ontological condition in which humans and other-than-human entities are already inextricably entangled through material, temporal and spatial interdependencies that precede any deliberate design decision. When biodesign artefacts are crafted to host spontaneous colonisation (e.g., by lichens, mosses, microalgae, fungi, insects and microbial communities), relationality is not defined by an immediate, instrumental exchange of services between species, but by the gradual recognition that design outcomes are co-produced by multiple agencies and temporalities, some visible and charismatic, others microscopic and unnoticed. In biodesign's approaches, such as bioreceptive design (Cruz and Beckett 2016; Pollini and Rognoli 2021), this ontological state of interconnection becomes perceptible in practices that deliberately stage "life-enabling" artefacts and environments, conceived not as inert substrates but as participants in metabolic, ecological and experiential processes that unfold over extended durations.

In design studies, the concept of "becoming-with" multispecies enriches the discourse on more-than-human relations towards novel practices of making, thinking and becoming (Nicenboim *et al.* 2024). Moreover, in posthuman and more-than-human design, proximity has been highlighted as the base of relational thinking, as the practice of designing-with aims to facilitate and intensify interspecies encounters and entanglements (Wakkary *et al.* 2025). Thus, relationality compels biodesign to embrace an ethics of entanglement, in which artefacts serve less as endpoints of human intention and more as enduring invitations to foster coexistence through sustained, open-ended participation across species, scales and temporalities.

Discussion through case studies

Building on the authors' plural professional backgrounds and their situated understanding of reconciliation in biodesign, this section examines how each principle offers a distinctive yet interconnected pathway for reimagining practices of engaging with biology towards more ethical, regenerative and multispecies forms of coexistence.

Case studies drawn directly from the authors' own design projects will serve in this section to reflect upon Restoration, Reciprocity and Relationality as guiding principles to discuss the projects' Reconciliation potential. Case studies serve here a dual

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methodological function; rather than operating solely as illustrative examples, they constitute the primary empirical and reflective material through which the principles of Reconciliation are interrogated and developed. This approach is grounded in a practice-based research paradigm (Eisenhardt 1989; Rowley 2002). In fact, the authors' embodied engagement with living materials and multispecies collaborations across these projects provided a first-hand epistemic vantage point, allowing insight to emerge from within the practice itself. The case studies are also visually discussed below through a table that highlights the principles and proposes guidelines involved: where the principles are highlighted in blue when strongly implicated and in white when they are only marginally or not applicable.

As such, the reflection on the case studies has been a generative source for the Reconciliation framework that will be discussed and presented in the following section.

Five case studies will be described and discussed in relation to the three principles, highlighting strategies adopted and outcomes, in an attempt to define recursive design strategies and guiding research questions that can inform and support Reconciliation principles in the biodesign practice.

Fungal biohybrids as habitat infrastructures (Ilgün, since 2018)

This study traces a research-by-design trajectory in fungal biohybrid architecture, focusing on ecological, technological and social relations among insects, humans, fungi and other microorganisms. Across the projects, wood-rot fungi operate in two roles: as cultivated performance components for human-defined aims, such as insulation, biodegradability, thermal regulation and material transformation; and as living infrastructural agents that require suitable substrates, habitats and ecological conditions to persist ().

The trajectory begins with hypothesis-driven design for honeybee housing and gradually expands toward wild bees, terrestrial insects, local fungal ecologies and more situated practices of care. Rather than presenting wild fungal foraging as the hyperlocal sourcing of the mycelial material cultures at the logical starting point, the sequence follows how the research actually developed: from technical restoration-oriented prototypes toward a more relational understanding of organisms' needs, origins, dependencies and capacities to respond. In this work, co-design is understood not only as collaboration among human experts, but also as a negotiation with the biological and technological conditions that shape multispecies cohabitation.

Together, the projects develop a methodology of bio-architecture for decay-dependent organisms. This methodology moves between controlled fabrication and open-ended collaboration with human and nonhuman others, contributing to reconciliation ecology through multiple contexts rather than a single design outcome. Reconciliation begins here with often-undermined organisms: insects, fungi, microbes and other invertebrates that are frequently excluded from human-managed environments, despite their foundational role in terrestrial ecosystems.

Mycelial Beehives were developed within the HIVEOPOLIS project (Ilgün *et al.* 2021; Ilgün and Schmickl 2025) to investigate fungal composites in beehive architecture. Five full-scale 3D-printed prototypes were tested outdoors for weathering, wildlife interaction and honeybee inhabitation across three seasons. The structures used inert scaffolds, including wood-filled home-compostable filaments and fiber-clay elements, combined with hyperlocal lignocellulosic residues to sustain living fungal matrices. The aim was to move away from conventional industrial apiculture materials and toward a bio-integrated hive system that could interact with the colony's thermal and microbiological environment. At this stage, restoration was the main guiding principle. The design addressed Western honeybees (*Apis mellifera*), wood-rot fungi and secondary residents such as the healthy nest microbiome and saproxylic insects through increased porosity, habitat-specific geometries and biodegradable material systems. Yet the project, in the time spent with the bees, especially opened questions of reciprocity and relationality. For instance, the hive was not designed around honey extraction, but as a wilder dwelling for domesticated honeybees, intended to support colony health, reduce intrusive management and allow less frequent physical disturbance. Although these questions could not be fully explored within the pre-defined structure of the EU-funded project, they were already incorporated in the design decisions.

The I.N.S.E.C.T. Wall Twin (Parker *et al.* 2023) extended this biofabrication approach into an academic co-design workshop format. Building on the Mycelial Beehives and the earlier Living Arch installation at Kunsthaus Graz (Ilgün *et al.* 2022), the project was realised in Newcastle upon Tyne during the I.N.S.E.C.T. Summercamp 2022 (Keune *et al.* 2023). It combined clay 3D printing, mycelium composites, parametric modelling and free-form crocheting, bringing together digital fabrication, hands-on improvisation and solid-state fermentation. Due to the compressed nine-day timeframe for design, printing, fungal growth and assembly, the project used a ready-made fungal material mixture prepared by Osmose Studio. This mixture included a commercial wood-rot fungal strain and substrate optimised for material production. In the Wall Twin, the fungal component was intended to act both as a living material and as an insect attractant through volatile compounds, while also contributing to insulation and potentially providing burrowable microhabitats for native wild bees in northern England.

As a critical making process (Ratto 2011), the project linked fabrication, cultivation, textile practice and ecological monitoring to broader social and ecological questions. The use of a commercial mycelium mixture was a practical solution, but later became an object of critique. Ready-to-use biodesign materials can support rapid experimentation, yet they can also distance designers from the ecological origins, cultivation practices and multispecies relations that such work aims to foreground. The project also addressed the social accessibility of biohybrid making by combining advanced digital fabrication with handicraft, especially crocheting and collaborative material improvisation. In this sense, reciprocity appeared not only between organisms and materials but also among participants with different forms of expertise.

Being<>Beecoming (Ilgun *et al.* 2023) was developed as a small, semi-permanent urban living laboratory inspired by the I.N.S.E.C.T. Wall Twin. It used clay 3D printing and a locally produced fungal strain native to Austria, rather than a commercial strain optimised for material production. The project created habitat niches for organisms associated with clay, soil, wood decay and urban microhabitats.

Unlike the previous prototypes, Being<>Beecoming was embedded in an already existing urban site. Installed at Club Hybrid in Graz, it became part of a wild microtope that had developed over two years within an artist-led architectural setting. The installation added modular, stackable clay components with varied internal geometries, creating cavities, surfaces and sheltered zones for local insects, fungi and other small organisms. The structure was shaped through collaboration with artists, workshops, public activities and

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perception walks. Over approximately six months, the project allowed designers and collaborators to observe how insects and visitors interacted with, modified, avoided, or inhabited the structure. When the site later underwent urban transformation, the pieces were moved to the Botanical Garden Graz. This project became an intermediate step between restoration-oriented prototyping and a more relational, public and site-responsive approach.

Learning by Foraging (2023) took place during the second year of the I.N.S.E.C.T. Summercamp (Keune *et al.* 2024) as part of the Critical Making focus group. Unlike the previous projects, it did not begin with a designed object or technical artefact. Instead, it focused on the upstream biological processes of fungal biodesign: slow sourcing, foraging, isolation in a self-organised kitchen lab and cultivation of wild fungal strains from Bidstrup forest, the site of the summer camp.

This project shifted attention from fungal materials as products to fungi as situated living beings. Participants learned how to encounter, collect, isolate, cultivate and care for fungi before translating them into design materials or ecological functions. The process also made visible the skills, time and ecological knowledge required for community-led fungal cultivation. Within this trajectory, Learning by Foraging represents the clearest move toward relationality with fungi. It was not primarily framed through restoration or reciprocity, but through the practice of learning how to meet fungi in the places from which they emerge.

Across these case studies, reconciliation operates on several levels. First, it takes place between digital fabrication and craft-based making, combining computation, automation and repeatability with improvisation, embodied knowledge and situated material response. Second, it takes place between humans, technologies and nonhuman beings, including wood-rot fungi, honeybees, wild bees, microbes and terrestrial insects. Fungal fermentation is therefore approached both as a biotechnological process and as an art- and craft-based practice. This framing moves fungal biodesign away from technosolutionism and toward critical making that is useful for practitioners, students, teachers and researchers working with fungal biotechnology. Digital manufacturing remains important, but it is used through a mode of "fragile computing" (Rigobello and Ayres 2021), which acknowledges dependency, uncertainty and the possible refusal of living systems, land-based practices and locally available resources. Restoration is the entry point of the trajectory. In the early projects, it appears through habitat engineering, bio-integrated materials engineered to attract native symbionts and support native biodiversity and attempts to repair disrupted relations among microbes, insects, fungi and human-managed environments. Over time, this restoration-oriented approach opens toward reciprocity and relationality. Reciprocity appears through metabolic and structural exchanges: fungi transform substrates, materials provide habitat, insects inhabit or modify structures and designers respond through observation and adaptation. Relationality emerges more gradually, through fieldwork, collaboration and lived experience with fungal structures, bees, insects and places. Designing fungal biohybrids outdoors requires attention to growth, decay, weathering, occupation, refusal and disappearance. This shifts the work from a solution-driven model toward a reflexive practice of learning with living systems (Figure 1).

Living jewels (Paoliello, since 2022)

Living Jewels is an ongoing handcrafted biodesign project that explores the direct interaction and a form of situated and asymmetrical collaboration between humans and living organisms, primarily lichens and mosses, in combination with wood and simple support structures. The aesthetic and interactional goals are largely set by the human, while the organisms participate through their ongoing biological needs, growth, dormancy and response to care, in combination with wood and simple support structures. Conceived as evolving artefacts, these pieces transform over time in response to humidity, light, temperature and the care provided by the wearer.

As modern humans often spend long periods indoors, in dry and darker environments, the jewel makes the needs of lichens and mosses directly perceptible: it raises questions about whether the warmth and sweat of the body can provide moisture, whether the wearer must periodically expose the piece to rain, mist or brighter conditions and how such requirements may alter everyday behaviour. Because the organisms are worn close to the body, their dryness or vitality can be felt almost like a second skin, creating an embodied sense of responsibility comparable to noticing when one's own skin needs cream or when the body needs more water. Each piece requires constant maintenance and attention, positioning the jewel as a mediator between nature and culture.

The project frames design as a space of multi-species coexistence, in which biological processes shape material and symbolic dimensions. Instead of producing utilitarian objects, Living Jewels fosters relationships and encourages reflection on care, interdependence and temporality. By embracing unpredictability and growth, the design moves away from logics of control and permanence, towards cultivation and co-evolution with living systems. Reconciliation is expressed through the reintroduction of living organisms into everyday artefacts, reactivating ecological awareness on an intimate scale. Reconciliation, here, becomes a continuous practice of attention, responsibility and interdependence between human and non-human life. Reciprocity operates through continuous care: the user sustains the organisms, while their development reshapes the object's form and meaning. Relationality emerges in multi-species co-creation, recognising lichens and mosses as active participants.

Beyond its specific material and experiential qualities, Living Jewels contributes to broader discussions in biodesign and more-than-human design by highlighting care as a primordial mode of multispecies interaction. While existing approaches, such as bioreceptive design and biofabrication, often focus on material performance or ecological integration, this project directs attention to intimate and sustained interaction at the body scale. In doing so, it reframes biodesign artefacts not as passive substrates for colonisation or functional systems, but as relational interfaces that require ongoing human participation.

This perspective extends current understandings of reciprocity in biodesign by situating exchange not only in metabolic or ecological terms, but in daily practices of maintenance, attention and attachment. At the same time, it deepens relationality by demonstrating how multispecies awareness can emerge through embodied experience rather than abstract ecological knowledge. Within the proposed reconciliation framework, Living Jewels highlights how small-scale, situated interventions can activate continuous processes of co-evolution, suggesting that reconciliation may operate not only at infrastructural or environmental scales but also through intimate, affective and temporal forms of engagement (Figure 2).

Designed wilderness: minimum viable ecosystems (Pollini, since 2024)

This project applies Bioreceptive Design to create a set of bioreceptive hand-formed sculptures made of unglazed red clay; the

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design features textured grooves, niches and organic contours that provide shelter and sediment, thereby kickstarting minimal, self-sustaining ecosystems (Pollini 2026). When placed outdoors, these sculptures undergo surface transformation via biofilms and species interactions that pioneer pathways for slower, spontaneous colonisation. The designer's input yields rapidly to nature's variability: moss and lichen transplants might fade as insects colonise, dust settles and biofilms pave the way for microalgae and beyond, restarting a self-sustaining cycle of situated life. This is evident from an aesthetic perspective and from the presence of various species on the artefacts over time. Aesthetically, the initial input is created through the sculpture and the planting of local cryptogams. After a few months, the sculptures appear bare and inert, but over time, a green patina begins to form on their surfaces, as if the objects' surfaces bloom according to different criteria: those of situatedness and the coexistence of local organisms. Various invertebrates and insects visit the sculpture temporarily or permanently, leaving traces and altering the microcosm that the sculpture tends to become over time.

Despite its potential as a restoration strategy to enhance biodiversity, the aim of this project is mainly to foster relationality through sensory attunement and a sense of belonging through a multispecies relational approach over time (ibid.). The project's outcomes are mainly based on the co-authorship of the bioreceptive artefact over time. In this project, no targeted species are planned in the conceptual phase of the bioreceptive design, but the sculptures aim to serve more as a revelatory space for humans to acknowledge who else is living in the surroundings and who is interested in interacting with the bioreceptive piece. Species imprint unpredictably over years, humans attune through multisensory noticing, yielding participatory processes that blend multispecies craft, slowness and co-designed spaces.

Bioreceptive Design is generally oriented toward optimising surfaces for targeted organisms; even multispecies-oriented biodesign frameworks, including those that foreground co-authorship and open-ended processes (e.g., Cruz and Beckett 2016; Groutars *et al.* 2024; Pollini and Rognoli 2021) typically retain a degree of species intentionality, positioning the designed artefact as a host environment calibrated to support specific biological actors. *Designed Wilderness* departs from this logic: rather than optimising toward a targeted species or a measurable biodiversity outcome, the project deliberately suspends species prescription and repositions the bioreceptive object as a revelatory device, one whose primary function is not ecological performance but the cultivation of human sensory attunement, situatedness and multispecies belonging. In doing so, it shifts the focus of the artefact's value from biological productivity to the relational and phenomenological processes it makes perceptible over time. This reframing toward slow design, other-than-human craft and participatory ecological aesthetics aligns the project more closely with the multispecies design discourse, being concerned with noticing rather than with a performance-driven trajectory (Figure 3).

Ossigeno: biofabrication for urban biodiversity (Brunelli, 2023)

Ossigeno is a biofabricated and bioreceptive project aimed at enhancing biodiversity and multispecies relationships in urban environments. The project is developed using a circular biofabricated material produced through biological processes, specifically biomineralisation, mediated by selected cyanobacteria, which, through photosynthesis, produce calcium carbonate that acts as a natural binder to create a new material from marble waste (Marseglia *et al.* 2026). The project and its material properties are designed for 3D printing and optimised to support spontaneous biological colonisation over time, including mosses, lichens and insects, which contribute to regenerative ecological processes that can improve biodiversity and air quality in urban environments.

Implemented as modular urban elements, the project explores how design can activate ecological processes and enable relationships between human and non-human species. In this case, restoration emerges through the introduction of bioreceptive urban design elements that create suitable environmental conditions for spontaneous colonisation by living organisms. Reciprocity is expressed in mutual exchange between design and living organisms: the designer creates habitat, while living organisms contribute first by providing specific material properties and then to CO_2 fixation as well as functional and aesthetic transformations through biocolonisation over time. Relationality emerges both from the co-creation of the material through the action of cyanobacteria and from the human/non-human relationships that the bioreceptive elements promote and sustain over time.

Ossigeno redefines urban furniture not as static products, but as continuously evolving relational infrastructures, shaped both by seasonal transformations and biocolonisation processes linked to the bioreceptivity of the material and, above all, by the ongoing interactions among humans, microorganisms, spontaneous colonising species and urban ecosystems that emerge and develop over time. The project develops through multispecies co-evolution and interdisciplinary integration of knowledge. Through the collaboration between Design and Biology, Ossigeno expands the exchange between human and non-human actors, including the co-production of the biofabricated material. The hybridisation of different disciplines, together with the action of cyanobacteria through biological processes, gives rise to a potentially living material whose functional and aesthetic properties continuously transform and evolve over time through the activity of living organisms and environmental conditions. Ossigeno thus conceives urban furniture as an open and dynamic process, able to generate environmental benefits like CO_2 fixation and to activate ecological and relational transformations between humans, materials and living organisms (Figure 4).

Brazzein: industrial biotechnology and the reciprocity gap (Marco G. Casteleijn)

Representing the molecular and industrial scale of the biodesign spectrum, this case study examines the production of brazzein (Ming and Hellekant 1994; Mojzita *et al.* 2025), a high-potency sweet protein (Assadi-Porter *et al.* 2008) naturally found in the West African Pentadiplandra brazzeana fruit. Utilising precision fermentation and synthetic biology, the process decouples genetic sequences from their botanical and cultural origins to produce a sugar alternative in microbial cell factories (Izawa *et al.* 1996; Kant 2005). Precision fermentation is an industrial process that harnesses microorganisms as cell factories to manufacture molecules with a precision that can sometimes be challenging or impossible to achieve with chemical synthesis (Plummer *et al.* 2026). The process utilises Digital (genetic) Sequence Information (DSI), a frontier in biotechnology that allows for the advancement of global health goals (WHO 2015), such as glycaemic neutrality without the

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ecological footprint of traditional agriculture (WWF 2004 and 2009). While the expiration of original patents places this specific genetic data in the public domain, the project highlights a pivotal shift in the industry: moving from the purely technical optimisation of biological assets toward a more integrated model. This modern approach seeks to harmonise high-efficiency industrial production with the spirit of international accords, ensuring that the global bioeconomy functions as a scalable, universal tool that respects its original biological and cultural foundations.

While genetic information, such as the brazzein sequence, can be subject to patenting, the Nagoya Protocol (Nagoya 2011 and Watanabe 2015) establishes protocols that ensure benefits derived from the use of genetic resources are returned to the communities that provided them. This has resulted in a pivotal shift in the biotech industry: moving from the purely technical optimisation of biological assets towards an approach which seeks to harmonise industrial production with the spirit of international accords. The intention of joining the Nagoya Protocol ensures precision fermentation could function as a scalable, universal tool that can respect the biological and cultural origins of genetic resources. In other words, under this accord, material of plant, animal, microbial, or other origin (e.g. DNA, RNA, metabolites or proteins), containing functional units of heredity that have actual or potential value, is no longer seen exclusively as raw data, but rather as part of a sustained partnership that intends to prioritise restorative benefit-sharing with source communities (Nagoya 2011).

In this context, the potential for reconciliation is challenged by the tension between functionalist efficiency and the reciprocal integrity required between the biological source and the final product. While precision fermentation of brazzein achieves a form of abstracted reciprocity by mitigating planetary-scale harms by reducing land-use and carbon emissions (Obayomi *et al.* 2026), it identifies a critical design gap regarding specific, local reciprocity. However, from a restorative perspective, precision fermentation projects achieve a planetary-scale "intentional repair" by replacing land-intensive sugar cultivation with low-footprint microbial production, reducing CO_2 and water use. Finally, the ongoing fermentation process does not automatically produce a relational practice. It can be approached mechanically, as a technical workflow of inputs, especially at very large-scale fermentations. On the other hand, forms of relationality are maintained in the laboratory and smaller-scale fermentations through sensorial attunement. The fermentation operator engages in a participatory exchange by monitoring growth curves, visual inspections, smell and metabolic stability, where the microbe's biological needs function as primary design constraints. These engagements can be rather individual. While industrial scaling naturally prioritises sequence optimisation and speed, there is a recognised risk of decontextualising genetic resources from their cultural origins (Amusan 2016). To build upon the foundations of the Nagoya Protocol, the industry can move toward a model of benefiting-with-life. This involves embedding an Ethical-Relational layer into the biotechnological lifecycle, treating genetic resources not just as raw data, but as part of a sustained partnership that prioritises restorative benefit-sharing with source communities (e.g. by addressing historical burdens of sugar production (Bosma 2023) or health problems in sugar production (Stanhope and Weinstein 2025). By utilising the proposed framework as an analytical lens, a critical Reciprocity Gap emerged: while technical efficiency is maximised, the connection to the biological and cultural source is often severed. This insight demonstrates how the framework moves beyond descriptive optimisation toward identifying potential ethical gaps in industrial practices (Figure 5).

Design for reconciliation when engaging with biology

The case studies presented here have been selected to represent the full methodological spectrum of biodesign: from macro-scale urban interventions (I.N.S.E.C.T. Wall) and intimate-scale wearable artefacts (Living Jewels) to molecular-scale industrial biotechnology (Brazzein). This diversity allowed the discussion of the three principles against different levels of "aliveness" and "visibility," ensuring the principles of reconciliation are robust enough to guide creatives, scientists and industrial biotechnologists.

The individual case studies serve as a cross-disciplinary evaluative tool for the principles of Restoration, Reciprocity and Relationality; in fact, drawing from different disciplinary backgrounds, the projects demonstrated how the three principles hold across radically different modes of engaging with biology, thereby supporting their cross-disciplinary utility.

Based on reflexive thematic and case study analyses, we understand reconciliation as the negotiated alignment of human and non-human systems, grounded in the three core principles of restoration, reciprocity and relationality. Restoration serves as a baseline for the ecological framework, addressing the commitment to the intentional rehabilitation of biological structures and processes in areas identified as ecologically depleted. Reciprocity moves beyond compensatory repair toward an ongoing practice of multispecies exchange, in which humans and nonhumans participate in relationships of care and co-produce ecological conditions through interdependence, co-evolution and shared flourishing over time. Relationality acknowledges a situated sense of togetherness and responsibility toward both human and non-human others, grounded in the understanding that neither humans nor biological artefacts exist in isolation, but are embedded within interdependent ecological, material and social webs in which human-managed environments become sites of mutual co-evolution and multispecies coexistence.

Based on this understanding, this section proposes a framework for engaging with biology from a reconciliatory perspective. The main principles of restoration, reciprocity and relationality are discussed in terms of their key features, providing examples and guiding concepts to orient designers and scientists when discussing existing projects and conceptualising new ones. Furthermore, to clarify and facilitate the application of each strategy, we highlight a few guiding questions to conceptualise and plan biodesign projects and set reconciliation goals for biotechnology development (Figure 6).

In a reconciliatory context, ***restoration*** is reframed not only as the active engineering of ecological functions but also as the development of a "feeling of responsibility." Historically, in industrialised societies, the responsibility for restoration has been outsourced to specialised expertise and technocratic management, a top-down imperative for institutional repair that often displaces individual agency. As professionalised education creates narrow silos of expertise, individuals frequently lose their sense of direct responsibility, largely because they no longer learn about or interact with the specificities of the land they inhabit. However, design thinking transforms repair into a socially active profession. It progresses from the basic aesthetic "greening" of surfaces to a collaborative process of "intentional repair," in which the designer serves as a bridge between expert knowledge and community-led ecological care. This issue focuses on how local, socially placed acts

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Fungal Biodesign for Habitat Infrastructures of Insects (Ilgün, since 2018)

Principle	Strategy	Reconciliation outcomes
Restoration	Ecosystem engineering	Computationally designed porous scaffolds increase fungal penetration and release volatiles that support saproxylic biodiversity beyond the initial honeybee target.
	Design of regenerative systems	Biohybrid artefacts function as metabolic nodes, where local fungi convert site waste into bioreceptive habitats and, through decay, nutrient-rich soil.
	Bioremediation	Medicinal fungi are deployed in beehives as microbiome modulators, replacing chemical treatments with a nutraceutical approach to colony health.
Reciprocity	Mutualistic care	HIVEOPOLIS proposes a mutualistic system: fungi provide shelter and pathogen protection for bees, while bees maintain thermal stability that supports fungal growth. Reciprocity centres on human-initiated mutualism, with metabolic exchanges extending to other species through fungal by-products and spore dispersal, strengthening wider ecological networks.
Relationality	Sensorial attunement	Calibrating human attention to non-human temporalities through the smell of healthy decay and tactile sensing of microclimates _ *Learning by Foraging* and perception walks in *Being<>Beecoming*.
	Multispecies relationality	Recognizing fungal growth and insect decay as spatial drivers. Working with and caring for honeybees, and observing their interaction with mycelia, reshapes perception, values, aims, and temporality. Knowledge emerges through extended fieldwork.
	Multispecies participatory design	Treating swarming or substrate rejection as valid feedback. The "fragile computing" keeps the design open and responsive to non-human refusal.

Figure 1. The *Fungal Biohybrids as Habitat Infrastructures* case study is discussed in relation to the principles and strategies of the proposed reconciliation outcomes.

can trigger autonomous, self-healing processes in deteriorated ecosystems. From the case studies analysis, ecosystem engineering, design for regenerative systems and bioremediation resulted as recursive key strategies to enhance relationality. The path toward systemic healing begins by observing organisms that modulate resource availability, mirroring them through human equivalents like dry-stone walls and terrace farming; these environmental catalysts facilitate a form of ***Ecosystem Engineering*** that supports diverse micro-habitats. When we create abiotic and bioreceptive artefacts that initiate life systems capable of evolving autonomously, we move toward a comprehensive ***Design of Regenerative Systems*** (Pollini and Rognoli 2024). Taking inspiration from regenerative farming and rewilding, these interventions trigger a biological succession that eventually requires no human intervention (Savory and Butterfield (2016)). Implementation of the designed material assemblies in the field becomes both construction and investigation. Diverse people work together to build, observe and adapt the intervention via distributed critical making (Ratto 2011). In situ performance becomes crucial; the technical artefacts are subjected to weather, insects, fungi and human use, yielding insights that cannot be obtained in controlled circumstances. Agency is spread among different species and populations. This joint shaping of the intervention increases both ecological sensitivity and social investment. Such active engagement further enables nature's innate ability to self-heal by, for example, neutralising toxins, a process of focused ***bioremediation*** exemplified by mycoremediation (Stamets 2005) that transforms technical solutions into community-led remediation rituals. Ultimately, by framing these methodologies through design thinking, we transfer responsibility for rewilding from the "expert" to the "citizen-steward," making ecological repair a visible and shared cultural activity.

To support the principle of restoration, two fundamental questions emerged: *Which damaged, missing, or degraded ecological conditions does the design intervention aim to restore?* (e.g., soil structure, moisture retention, nesting opportunities, microbial diversity, deadwood availability, shelter, food resources, or habitat connectivity). *How does the intervention support specific organisms, ecological relationships and regenerative processes over time?* Moreover, complementary sub-questions were identified for each strategy: Ecosystem engineering – *What specific environmental conditions does the intervention generate to support other species?* Design for regenerative systems – *How can a localised intervention trigger broader ecological effects over time?* Self-repair and bioremediation – *How does the intervention support nature's capacity to self-heal, while ensuring that human participation enables rather than replaces ecological regeneration?*

If restoration sets an ecological baseline and relationality describes interconnections, ***reciprocity*** is about how exchanges grow over time, it is about designing interactions. In a reconciliatory project, reciprocity means more than just compensating for harm or adding "green value." Human actions must support the basic needs of other species: their metabolism, space and reproductive capacity and human well-being depends precisely on these conditions. To move from these foundational concepts to actionable strategies, Groutars *et al.* (2024) describe reciprocity in

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Living Jewels (Paoliello, ongoing since 2022)		
Principle	**Strategy**	**Reconciliation outcomes**
Restoration	/	Living Jewels creates portable micro-ecosystems for lichens and mosses, without system-level restoration. Its contribution is domestic-scale cohabitation and care.
Relationality	Direct exchanges	An indirect exchange occurs: wood provides substrate; organisms provide growth and transformation; humans provide care.
	Mutualistic care	The project builds on existing mutualisms (lichen symbiosis; moss supported by wood). Organisms remain autonomous, while humans act as environmental mediators.
	Kin-based cooperation	The piece relies on the user as caregiver, fostering ongoing ecological responsibility. The object operates as a shared multispecies system.
Relationality	Sensorial attunement	The project fosters multisensory awareness through visible growth, material change, fragility, and care, heightening attention to environmental conditions and biological cycles.
	Multispecies relationality	Living Jewels is inherently multispecies. Humans, lichens, mosses, and wood coexist in an ecological, symbolic, and material relational system.
	Multispecies participatory design	Living organisms participate through growth and transformation. The design remains open-ended and unpredictable, though their participation is not intentional.

Figure 2. The *Living Jewels* case study is discussed in relation to the principles and strategies of the proposed reconciliation outcomes.

biodesign as deliberately shaping multispecies interactions for co-adaptation over time. Building on this foundation and on the case studies analysis, this article highlights three operational strategies of reciprocity: direct exchanges, mutualistic care and kin-based cooperation. The first strategy, ***direct exchanges***, is based on evolutionary theories that posit that repeated interactions foster cooperation (Axelrod and Hamilton 1981; Trivers 1971). In nature, this includes grooming symbioses, mating gifts and other repeated interactions strengthened over time. In biodesign, direct exchanges involve creating artefacts that allow organisms and materials to visibly affect one another. For example: surfaces for lichens or mosses, microbial systems that clean air while gaining nutrients and pollinator-friendly façade features. In each case, exchange is material, repeatable and adaptive. ***Mutualistic care*** sustains metabolic interdependence. According to Karana *et al.* (2020), it is a two-way, evolving relationship: humans help living artefacts thrive. Living artefacts need ongoing attention and adjustment. Care is a core part of how they work, not just upkeep and creates a feedback loop in daily practice (Dal Falco *et al.* 2024). Humans adjust light, humidity and nutrients; organisms respond with growth, change, or new experiences. This resembles ecological models in which "biological currencies" (e.g., nutrients, protection and shelter) are exchanged between partners (Bronstein 1994). Finally, ***kin-based cooperation*** spreads responsibility across time and groups. It is based on inclusive fitness and kin selection theory (Hamilton 1964), which suggests that working together helps family lines survive. In social insects, different roles help the colony last by investing in offspring. In biodesign, this thinking can guide how we care for shared spaces, pass on stewardship across generations and share responsibility for living systems in buildings and landscapes. Reciprocity is kept steady by cooperation over time, as humans support non-human life and help build lasting ecological resilience.

To support the principle of reciprocity, we propose three fundamental questions: *What is exchanged between humans, nonhumans, materials and environments and who benefits from these exchanges? How are these exchanges maintained, adapted, or withdrawn over time? What relationships, places, or communities are displaced or obscured by the intervention and how are they acknowledged or restored?* These questions inform three reciprocal design strategies: Direct exchanges – *What forms of exchange occur, where do they take place and how does the design support mutually beneficial conditions?* Mutualistic care – *Who or what sustains the relationship, and how is care distributed across living systems, materials and environments?* Kin-based cooperation - *How does the system support long-term cooperation, adaptation and ecological balance across generations and communities?*

These questions also show that reconciliation is not only a matter of designing better exchanges between humans and non-humans. It also requires examining the disciplinary, cultural and ecological conditions through which biological systems are made available for design. This is particularly important in industrial applications of biodesign, such as precision fermentation, where restoration may be claimed at planetary scales, or in the redesign of beehives that could be adopted by one of the world's largest industries: agriculture. In such cases, responsibilities, benefits and material consequences may remain unevenly distributed across

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Designed Wilderness: Minimum Viable Ecosystems (Pollini, 2025)

Principle	Strategy	Reconciliation outcomes
Restoration	Design for regenerative systems	The initial bioreceptive architecture is an input for the future spontaneous colonisation by random (non-targeted) species. The object is intended to become a future autonomous abiotic-biotic system.
Reciprocity	/	This project isn't aimed at mutualistic exchange, so the reciprocity aspect is secondary, if not absent. However, it could be argued that the sculpture offered to local agencies could enrich the human biophilic experience.
Relationality	Sensorial attunement	The project aims at enhancing the art of noticing, fostering the acknowledgement of local species and their way of inhabiting or profiting from the given environment
	Multispecies relationality	The project foresees a "slow biodesign" approach which requires a relational approach over time
	Multispecies participatory design	The project is aimed for multispecies open-ended design

Figure 3. The *Designed Wilderness: Minimum Viable Ecosystems* case study is discussed in relation to the principles and strategies of the proposed reconciliation outcomes.

local or regional contexts. Reconciliatory biodesign therefore requires attention to origins, asymmetries and irreversibility: At which scales does restoration occur, local, regional, or planetary and where do gaps emerge between benefits and responsibilities? If the system fails, scales uncontrollably, or is withdrawn, what forms of ecological, cultural, or relational restitution remain possible? These cross-cutting questions move the framework beyond single design interventions and toward reconciliation between disciplines, sites, cultures and scales of responsibility.

As seen, ***relationality*** is here intended as an ontological state of co-existence and interconnection, leading to a foundational worldview shift that frames ecosystem-wide thriving. Relationality doesn't necessarily entail resource exchange or a mutual state, but it can facilitate humans' acknowledgement and enjoyment of otherness. From the case studies' analysis, sensorial attunement, multispecies relationality and multispecies participatory design resulted as key strategies to enhance relationality. ***Sensorial attunement*** to Nature is at the basis of practices grounded in the sensory perception of otherness, such as the art of noticing, described precisely as an attunement to non-human beings and natural systems through multisensory observation and situated awareness (Liu *et al.* 2018; Rosén *et al.* 2024; Tsing 2021). Designing for sensorial attunement to a target species or to a given environment might support a shift in how non-humans are perceived and acknowledged, enhancing post-anthropocentric worldviews. Relationality determines our ability to perceive, acknowledge and be together with other species. Multispecies relationality can occur in cross-species friendship (Dagg 2011). The bond occurring between dogs and cats is a tangible and frequent example, and the earlier the age of their first encounter, the better their amicable relationship will be (Feuerstein and Terkel 2008). In biodesign, the perceived agency of the organisms involved in the design process is evident when designers relate to them as co-performers (Camere and Karana 2018; Niinimäki *et al.* 2018) or are deliberately designing for sensory engagement (Ofer and Alistar 2023). The aliveness of biological agents in biodesign is emerging as a design feature (Karana *et al.* 2020), but it is also seen as an opportunity to reconsider the relationship between nature and culture, and to question the hierarchies that separate humans from non-humans, in those projects advocating a shift beyond anthropocentric perspectives toward more relational and inclusive approaches in biodesign (Keune *et al.* 2022). The push for a shift beyond anthropocentric perspectives toward more relational and inclusive approaches in biodesign is closely linked to the concept of ***multispecies relationality***. This idea, rooted in relational ontologies and explored mainly in multispecies ethnography, environmental anthropology and critical ecology, seeks to mend the disconnection between humans and nature by fostering ethical co-existence and producing new connections for collective striving for survival (Romm 2021; Riley *et al.* 2024; Silva-Garzon *et al.* 2022). In biodesign, organisms involved in the design process are often perceived as co-authors of the project (Collet 2021; Davidova 2017). Moreover, in the biofabrication process, a more creative and crafty approach facilitates relationality in the practice of growing and biotinkering (Pollini and Kääriäinen foreseen 2026), as well as relational temporal attunement with the organism

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Ossigeno: Biofabrication for urban biodiversity (Brunelli, 2023)

Principle	Strategy	Reconciliation outcomes
Restoration	Ecosystem engineering	Designed micro and macro-geometries create favourable conditions and habitat for the establishment of different living organisms such as lichens and mosses, fungi and insect.
	Design of regenerative systems	The system relies on spontaneous and self-regenerating biocolonisation processes
	Bioremediation	The photosynthetic activities of the organisms colonising the structure have a potential contribution to biodiversity enhancement and air quality improvement in urban environments
Reciprocity	Direct exchanges	The designer configures favourable conditions for biological growth, while living organisms contribute to thermal regulation and CO_2 fixation
	Mutualistic care	Cyanobacteria involved in the material creation continue, throughout their life cycle, to produce functional and aesthetic transformations without direct control by the designer
	Kin-based cooperation	The bioreceptive elements functions as a shared system between species
Relationality	Sensorial attunement	The project fosters eco-literacy among users through the observation of the growth dynamics, transformations, and biological processes of local species that colonize the elements
	Multispecies relationality	The project fosters human–organism coexistence by activating relational processes.
	Multispecies participatory design	Living organisms contribute both to material creation, by providing functional and aesthetic properties, and to the transformation of the elements through biocolonisation over time

Figure 4. The *Ossigeno: Biofabrication for urban biodiversity* case study is discussed in relation to the principles and strategies of the proposed reconciliation outcomes.

(Williams 2022). Efforts to reimagine multispecies commons position co-design and open-ended design as promising approaches for reframing collaborative and participatory design beyond human exceptionalism (Haldrup *et al.* 2022; Veselova and Gaziulusoy 2022). Increasingly, the field of participatory design (traditionally grounded in human rights and well-being) is interrogating the importance of entanglement theories and reconsidering its scope to include relationships with non-human living and non-living entities (Heitlinger *et al.* 2025). ***Multispecies participatory design*** can be considered whenever other-than-humans are given agency to participate in the making, whether through physical or aesthetic transformations at the surface, material, infrastructure, or system level. In multispecies participatory design, relationality unfolds over time, potentially crossing a multiplicity of agents, not because they have to participate in the process, but because they simply exist simultaneously, and their existence affects their shared landscape.

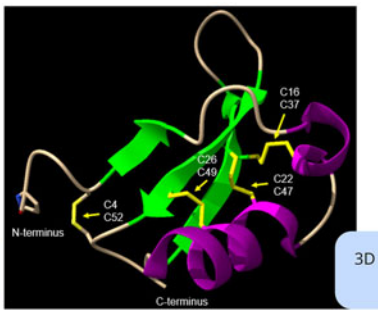
To support the principle of relationality, we propose two fundamental questions: *What forms of encounter does the design make possible between humans and other living beings?* (e.g., observing, sensing, caring, noticing seasonal change, responding to growth, decay, movement, sound, smell, or habitat use). *How does the design change human understanding, behaviour, or responsibility toward other species?* (e.g., by making hidden ecological processes visible, encouraging maintenance, slowing down interaction, enabling observation, or supporting shared use of a place). Sub-questions to inform more specific guidelines also emerged: Sensorial understanding – *Which senses does the design activate to help humans notice and respond to other-than-human life?* Multispecies relationality – *How does the design foster embodied awareness of living together with other species?* Multispecies participatory design – *How can nonhuman responses, preferences, or refusals shape the design process over time?* (Figure 6).

Bringing together principles and guiding questions, Figure 6 presents the reconciliation framework as an outcome of this section; this can be intended as a soft tool, based on a shared language across multiple disciplines, to familiarise oneself with the concept of reconciliation and to advocate reconciliation literacy for scientific and creative practices working with life. Moreover, it can serve as a guiding structure, offering a sufficiently grounded architecture to be operationalised across design education, practice and policy, based on three interconnected principles, each accompanied by concrete strategies and key reflective questions. In design education, the framework's guiding questions are directly legible as studio briefs, reflective prompts, or assessment criteria. Educators can use this plurality to invite students to locate their own practice within the restoration–reciprocity–relationality continuum, fostering a mindset of ecological negotiation rather than technical mastery alone. In creative and scientific practice, operationalisation requires translating the framework's ontological commitments into project workflows. The strategies and questions nested within each principle can function as a project audit structure, allowing practitioners to interrogate which dimensions of reconciliation a given intervention addresses and which it omits. This analytical function has practical value for design teams seeking to identify blind spots from the concept phase onward.

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Pentadiplandra brazzeana, native to the Atlantic coastal areas of Central Africa



3D model of the brazzein molecule



Made through precision fermentation

Precision Fermentation of Brazein (Mojzita et al., 2025)

Principle	Strategy	Reconciliation outcomes
Restoration	Design of regenerative systems	The project reduces land use, water use, and CO_2 emissions by replacing sugar cultivation with microbial production, lowering the planetary footprint of sweetness.
Reciprocity	Direct exchanges	Human operator of the process configures favourable bioreactor conditions for microbial production of brazzein.
	Mutualistic care	From erased to abstracted and situated reciprocity: abstracted reciprocity is expressed here by mitigating multispecies planetary-scale harms. Situated reciprocity refers to human global health gains, innovation must ensure fair socio-economic returns for West African stewards through integrated partnerships that make them active participants in the product's success.
Relationality	Sensorial attunement	Fermentation operators engage with living systems through monitoring growth curves, metabolic activity, and system stability
	Multispecies relationality	Living organisms participate materially through growth and transformation. However, participation is not intentional from the organisms' perspective
	Multispecies participatory design	The organisms' needs can be seen as design constraints inputs that shape the final environmental condition for growth. Moreover, in this case, we can argue that participation extends beyond microbes to regulators, source communities, scientists, and industry

Figure 5. The *Brazzein: Industrial Biotechnology and the Reciprocity Gap* case study is discussed in relation to the principles and strategies of the proposed reconciliation outcomes.

Moreover, the distributed authorship model suggested by the framework implies that practice-oriented operationalisation entails revising how authorship, time and success metrics are defined in professional deliverables. In policy-making, the framework's connection to existing regulatory instruments is already implicit in the paper's references to the EU Nature Restoration Law (2024), the Kunming-Montreal Global Biodiversity Framework Target 12 and the Nagoya Protocol. These provide ready institutional anchors through which the principles can be aligned with legislative requirements for biodiversity-inclusive urban planning, benefit-sharing in biotechnology and ecosystem restoration standards. More specifically, the framework's emphasis on situatedness and context-specific intervention resonates with the adaptive management logic increasingly embedded in restoration policy. Policymakers could operationalise the framework by incorporating its guiding questions as evaluation criteria in biodiversity impact assessments, competition briefs for public infrastructure, or funding calls for urban ecological design, thereby institutionalising reconciliatory intent without flattening it into compliance metrics. This work aims to give the framework traction beyond academic discourse, positioning biodesign as a field with direct institutional relevance.

We hope that the concepts emerging from this work can be mobilised to help align scientific knowledge with situated practices. These cases demonstrate reconciliation's potential to reorient biodesign from mitigation toward co-evolutionary infrastructure. Reconciliation transforms biodesign from a practice oriented towards mitigating impacts into a relational and ontologically committed practice, grounded in the coexistence and co-constitution between humans and non-humans.

However, we are aware that limitations persist. One limitation concerns the scope of the framework's validation, as it was tested exclusively on the case studies that also contributed to its formulation; therefore, further independent validation is required to strengthen its transferability. Empirical data on long-term biodiversity outcomes remain aspirational, constrained by project scales and durations. Future work must quantify multispecies flourishing through metrics like species richness and interaction networks. Other cosmologies must be included and pluriversalities incorporated; the criteria for project decisions and the limits of intervention must be clearly defined and rules for ecological restitution must be articulated. When it comes to scalability and industrialisation, we are aware of the tensions the proposed framework for reconciliation might entail; however, we believe that this study can offer an exciting opportunity to also consider industrial biotechnologies in terms of the reconciliation and quality of the communities they build. The Nagoya protocol, discussed in the precision fermentation case study, is an example that seeks to contribute to the integration of concepts of reconciliation into other critical decision-making tools that shape the industrial biotechnology sector. Being aware of such limitations, we present this study as a first attempt to articulate a positioning framework that can be further developed in future work. Rather than proposing a prescriptive toolkit, the framework serves as a

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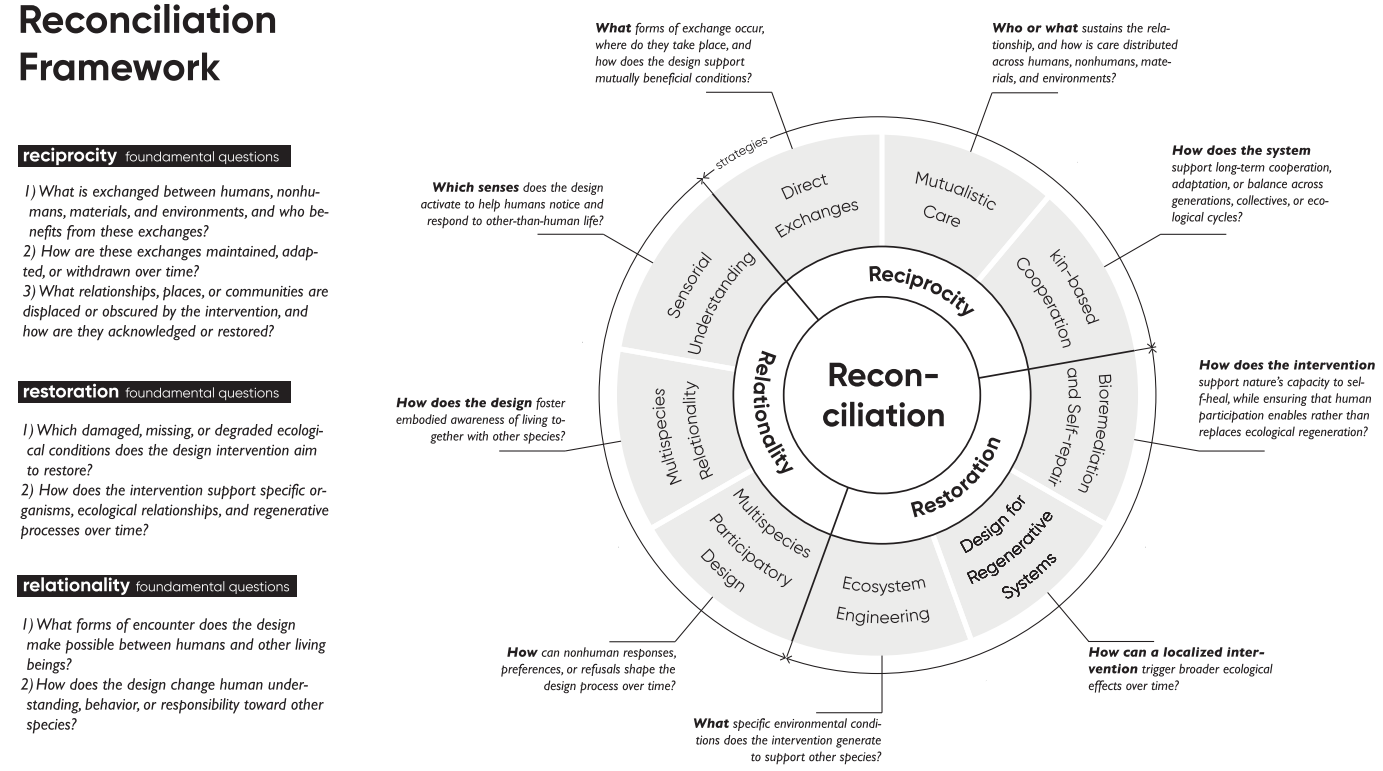


Figure 6. Set of principles, strategies and key questions to facilitate reconciliation processes in the context of biodesign.

guiding lens for design and scientific practice, offering principles and questions to inform context-specific methods, educational approaches, corporations and policy orientations. At the same time, our aim is to maintain an open and inclusive dialogue across bio-based technologies, as we consider reconciliation between disciplines a central pillar of this framework. Amid the great diversity of approaches shown by the case studies, we see an interesting common denominator in cultivating discussion on reconciliation. Together, these contributions position reconciliation as a generative framework for advancing more integrated, multispecies-oriented approaches in biodesign.

Conclusion

The study aims to illustrate how reconciliation manifests as a dynamic process in biodesign practice, revealing both strengths and tensions in applying restoration, reciprocity and relationality. Reconciliation reframes biodesign as a practice that negotiates human/non-human alignments, prioritising multispecies coexistence over extraction and control. By operationalising restoration as baseline repair, reciprocity as structured interdependence and relationality as ontological entanglement, the framework equips designers to foster regenerative environments amid fragmentation. The proposed framework, articulated through principles, strategies and guiding questions, therefore functions as a heuristic to help practitioners navigate these complexities.

From this perspective, the framework also points towards broader directions that remain to be further developed. In particular, slowness and temporal co-evolution emerge as structural conditions for reconciliation, where time is understood as the medium through which ecological relationships, care and multispecies adaptation become perceptible. At the same time, the framework itself serves as a collaborative, cross-disciplinary platform, foregrounding reconciliation not only between humans and nonhumans but also among disciplines, epistemologies and forms of expertise.

The case studies, used here as empirical and reflective insight for the final proposed framework, suggest the following design shifts: fungal habitats and bioreceptive artefacts exemplify ecosystem engineering that empowers non-human agency; sensorial jewels enact intimate kinship; the application of virtuous protocols in precision fermentation supports the ethical frontiers of scalability. Collectively, the case studies adopt a reconciliation lens, operating through continuous, situated and responsive relationships with non-human beings, recognised as agents, co-participants and co-regulators of the environment.

To conclude, the article proposes reconciliation as a guiding principle for biodesign, operationalised through the interconnected tenets of restoration, reciprocity and relationality, to foster multispecies coexistence amid habitat fragmentation. Drawing on the authors' diverse case studies, the work elucidates how these principles can manifest in practice, bridging ecological repair with ethical co-creation. Ultimately, reconciliation hinges on a distributed agency: the recognition that the responsibility to safeguard our co-evolutionary web is not restricted to the scientific community but is inherent to every participant in the modern world. Whether we are designers, scientists, engineers, citizens or consumers, we are all tasked with the active maintenance of the systems that sustain us.

Data availability statement. Data availability is not applicable to this article as no new data were created or analysed in this study.

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Note

1 Kunming-Montreal Global Biodiversity Framework, Target 12: "By 2030, transform the planning, development, and management of urban areas to promote biodiversity-inclusive urban planning and design, with the participation of local communities and integration of biodiversity considerations into economic and spatial planning." (Convention on Biological Diversity, 2022).

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