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Towards Regenerative Material Design and Innovation: Overcoming Multi-Level Barriers

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Abstract

The ecological impacts of industrial products are often locked in at the material design stage, requiring transformative changes to practices, mindsets and systems from the beginning of the innovation journey. This paper critically explores how such transformative shifts are being shaped by the application of regenerative principles to material design and innovation practices in the realm of entrepreneurship. It is based on a qualitative interview study with 12 material innovation companies. The study aims to understand the novel innovation practices they are fostering to catalyse regenerative and/or circular approaches that can address global plastic pollution – a major contributor to global GHG emissions. The analysis identifies seven perceived innovation barriers that complicate the full adoption of regenerative principles, including advocating for new product categories, educating B2B customers about novel materials and inventing appropriate scaling approaches. Overcoming these barriers requires mindset-related and systemic transformations, linking this research to broader innovation management, sustainability transitions and regeneration debates. The article concludes by articulating key insights and managerial implications for innovation leaders who are keen to further regenerative transitions through material innovations within (and beyond) their own organisations.

Keywords: Regenerative Design, Biomaterials, Material Innovation, Plastics, Systems Design, Sustainability Transitions, Innovation Barriers.

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1 Introduction

The plastics industry is the second-largest contributor to industrial greenhouse gases (Persson et al., 2022; Farrier, 2020; Hamilton & Feit, 2019). Every piece of (non-incinerated) plastic manufactured since the 1950s still exists today (Geyer et al., 2017), found in the most remote places (Napper et al., 2020; Peng et al., 2018) and in human blood (Leslie et al., 2022) while posing a threat to marine and plant life (Seuront, 2018; Xu et al., 2022). The lack of coherence between business, science, and policymakers regarding the standardisation of new materials is a significant concern (Fazey et al., 2020). Despite legislative measures across the European Union and the United States to limit certain synthetic materials, the production of plastics is projected to triple by 2050, with over 90 percent of plastics remaining non-reusable (Circle Economy, 2023; Geyer, 2020).

Design and innovation management play a major role in generating these harms since material selection, blending, and end-of-life management is estimated to account for 80 percent of environmental impacts (McAloone & Bey, 2009; Politowicz & Earley, 2009). It is clear, therefore, that organisations must consider material impacts as a critical aspect of their philosophy and innovate alternatives that can replace harmful materials while ensuring economic viability (Tushman & O'Reilly, 1996; Crossan & Apaydin, 2010). However, if not done carefully and holistically, the many complexities of addressing material impacts and introducing better alternatives can produce unintended consequences such as high energy consumption or the incorporation of (other) non-recyclable waste materials (Ljungberg, 2007). To tackle such challenges of future-facing material design that support planetary health, managers, designers and researchers, all need to develop novel competencies urgently, adopt alternative frameworks and re-examine their ontological assumptions on the relationship between society, economy and nature (Rittel & Webber, 1973; Reed, 2007b; Moriggi et al., 2020).

Although this general imperative is now crystal clear and rarely contested in principle, multiple barriers continue to stand in the way of alternative material innovations and systems in actual industrial contexts. Unfortunately, dominant frameworks, theories and concepts in the design, innovation management and sustainability fields offer limited guidance on overcoming such roadblocks. Design thinking, for its part, has been praised and widely disseminated as a strategic tool to develop product and service solutions while increasing end-consumer satisfaction as well as loyalty (Gonera & Pabst, 2019; Buchanan, 1992; Liedtka & Ogilvie, 2011). However, critics argue that it oversimplifies complex systemic problems and is often ineffective in solving real-world issues (Liedtka & Ogilvie, 2011; Sanders & Stappers, 2008; for an alternative, 'sustainable' design thinking approach, see Geissdoerfer et al., 2016). Meanwhile, innovation management has benefitted from research on common barriers and sources of resistance to radical and disruptive innovation that has examined how companies can overcome such barriers by shaping mindsets and introducing novel product categories, for instance (e.g. Tidd & Bessant, 2020; Barile & Savioano, 2018; Heger & Rohrbeck, 2012; Kock et al., 2015; Assink, 2006). Nevertheless, it is becoming recognised that conventional innovation management – or radical innovation in its usual, technology-focused guises – is no longer sufficient if the ultimate goal is to pursue regenerative materiality and new types of growth (Fazey et al., 2020) while dealing with complex systems to promote sustainable Earth system governance (Kanger & Schot, 2019; Raworth, 2017; Hansen & Von Oetinger, 2001).

The same issue of limited usefulness applies to the concept and field of sustainability that emerged as a response to the adverse consequences of an anthropocentric, exploitative approach to capitalism (Heikkurinen et al., 2021) from the 1970s and 1980s onwards (Gibbons, 2020). Indeed, many now argue 'sustainability' has reached its limits as a concept and is being used to perpetuate the status quo of mechanistic worldviews, human-nature separation, relentless ongoing destruction of the biosphere and resistance to more fundamental changes (du Plessis, 2012; Stoknes, 2014). This is why it is becoming harder for the developers and advocates of new material practices and production systems to rely on the sustainability literature and related innovation theories to chart a credible, life-enhancing path while addressing systemic barriers.

Offering novel possibilities in relation to the dilemmas of material innovators, the regeneration paradigm has begun to gain considerable traction recently, particularly in its design applications (Cole, 2012; Mang & Haggard, 2016). This alternative paradigm, influenced partly by Indigenous cultures and holistic worldviews common to many non-Western cultures, emphasises symbiotic engagement with living systems (Rodale, 1983; Lent, 2018; Descola, 2013). Drawing on Reed (2007b), Mang and Reed (2011), and Ichioka and Pawlyn (2021), regenerative design can be broadly understood as a process that *prioritises the evolution and thriving of whole living systems*. This often includes cultural, economic, geographic, climatic, and ecological aspects (Mang &

Reed, 2011) for regenerating 'socio-ecological systems'. A regenerative mindset views the Earth as a living system based on symbiotic interactions (Tsing, 2015) that co-evolves in specific ways (Albrecht, 2019; McDonough & Braungart, 2002; Wahl, 2016).

Despite the many conceptual, philosophical and systemic advances of the regenerative paradigm and related living systems theories, it is critical to note that these remain only partly helpful as a source of guidance and insight for designers and innovation managers. This is due primarily to the fact that *industry-specific empirical research* on real-world regenerative design and innovation processes and barriers remains scant in materials science (with the possible exception of regenerative architecture and agriculture). It is not sensible to assume that the transformative challenges of regenerative design and innovation are the same across all industries and sectors in all settings and contexts. We also know little about the specific new competencies, types of training and knowledge that managers need to cultivate in areas such as (regenerative) material design and how they can work based on whole-systems principles while receiving ongoing feedback through a conscious process of learning and participation (Reed, 2007b).

Based on original interview-based research, this study investigates the innovation practices of material science companies that seek to replace methods using extractive, degenerative materials with regenerative, bio-based or circular approaches. It examines the implementation of regenerative principles and identifies emerging barriers at the very frontiers of this field. Particularly, it explores the obstacles that materials science companies face in this pursuit and the prerequisites of implementing regenerative principles at the ideation and scaling stages. As such, our paper is relevant in relation to broader debates on sustainability transition and regenerative frameworks. To achieve these goals, the study draws on three complementary fields (design research, innovation studies and regeneration research) and is guided by three objectives:

(1) To critically review relevant literature, discussing the emerging paradigm shift from sustainability to regeneration while specifying how it is being applied to design as well as the relevant competencies needed for realisation.
(2) To investigate selected material science companies through an interview-based study, unpacking the salient obstacles they face in actualising regenerative principles across the ideation and implementation stages of their idea journeys (Perry-Smith & Mannucci, 2017).
(3) To offer a reflective discussion on critical findings, highlighting the development of competencies for whole-system thinking and a shift in mindset and collaboration among stakeholders during the scaling process, followed by managerial implications for adopting regenerative principles, innovation and integration.

We argue that it is not only essential for companies to prioritise positive ecological impacts over profits through regenerative material innovation but also that doing so is *possible and feasible*, provided that the related barriers are studied in more depth and addressed inventively from a systemic and context-sensitive mindset.

2 A new nature-based ontology for design and innovation

This section discusses the impact of anthropogenic thinking on design practices, the limitations of the sustainability paradigm, and the emergence of regenerative design as a more holistic approach that considers the interconnections between human and natural systems. First, our current epoch, the Anthropocene, is defined by human activity's impact on the biosphere (Crutzen, 2002). One major downside of this concept is that it may itself help perpetuate the Western mindset that treats the Earth as a collection of resources to be exploited for capitalist gain (Haraway, 2015; Malm, 2015). The pursuit of wealth and growth generated through capitalism has caused a degenerative industrial cycle that exploits natural resources and returns waste to nature, contributing to planetary degradation (Reed, 2007b; Rockström et al., 2009; Jackson, 2009; Meadows et al., 2018; Barbier, 2005). This mindset is rooted in mechanistic philosophies (Bacon, 1855; Descartes, 2000) that have furthered the exploitation of natural resources and the cultural dissociation from the living environment (Capra, 1996; Cole, 2012; Rees, 1995). Anthropocentric thinking significantly impacts the design of products and systems and has been identified as a significant contributor to socio-ecological problems (Shapira et al., 2017; Manzini, 2006). Shedroff (2009) argues that design is responsible for addressing environmental concerns and emphasises the importance of considering the entire life cycle of a product, from its creation to its disposal. Here, co-creation and collaboration between companies and their stakeholders (e.g. communities, suppliers, governments, investors, B2B customers and end-consumers) can lead to alternative products and services that address environmental concerns and promote positive social and economic outcomes (Bowen et al., 2018; Manzini, 2006).

The sustainability paradigm and its application in design have been widely adopted across sectors, focusing on current resource uses and practices that are not detrimental to present or future generations (Brundtland, 1987; Kidd, 1992). In pursuit of these goals, scholars have increasingly focused on sustainable innovation and its management over the past decade (Schiederig et al., 2012). However, sustainability lacks a common basis for experts to define sustainable practices that can be applied globally (Gladwin & Newburry, 1997). This limitation has led scholars to question the paradigm's value, considering its capacity to perpetuate existing mechanistic patterns, thereby creating resistance to change (du Plessis, 2012). Exploring how design practices can evolve in an interconnected world is said to be crucial for sustainable innovation and management (Schiederig et al., 2012). Therefore, as Daly and Daly (1973) argue, organisations must align their values with those of nature and give back more than they take from the ecosystem's regenerative and absorptive capacity. This implies a need to break with conventional economic practices that are commercially but environmentally harmful (Wahl, 2006).

The concept of regenerative design has gained attention among scholars and managers in recent years, shifting towards a more holistic process that considers the interconnections between human and natural systems (Reed, 2007a; Wahl, 2016; Lent, 2018). While sustainability remains a crucial dimension of this paradigm, regeneration offers a more symbiotic approach that seeks not just to limit the damage but also to *improve* the health of humans, ecosystems and the planet (Cole, 2012; Mang & Haggard, 2016; Reed, 2007b). The definitions provided by Reed (2007b), Mang and Reed (2020), and Ichioka and Pawlyn (2021) all emphasise the importance of resilience in regenerative design. They focus on the evolution of the whole system by understanding the inner workings of ecosystems to regenerate socio-ecological wholes that support the flourishing of 'all life for all time' (Ichioka & Pawlyn, 2021).

To re-examine human-nature ontologies and regenerative organisations, it is necessary to overcome the biases of Western perspectives (Rosiek et al., 2020; Hahn & Tampe, 2021) and recognise that Indigenous peoples successfully steward territories that account for approximately 80 percent of the planet's biodiversity (Descola, 2013; Royal, 2005; Hickel, 2020; Raygorodetsky, 2018). Regenerative design offers a solution to address socio-ecological challenges and opportunities for human-nature symbiosis and structural dynamics. To achieve this, regenerative design requires the active symbiotic participation of multiple beings while considering the long-term effects of design decisions. This approach prioritises human and environmental health by using materials with minimal environmental impact and considering the long-term impacts of design choices

(Papanek, 1971; Ljungberg, 2007). By embracing the uncertainty and chaos of the changing world through new forms of connection between humans and living systems, regeneration and design can create new relationships between humans and nonhumans (Haraway, 2016).

3 On common innovation and design barriers

This section outlines three general sets of challenges that we anticipate most material science companies will face during their innovation journeys (regardless of industry). By briefly previewing these challenges, we create a basis for situating and analysing the findings from our empirical study in subsequent sections. First, pursuing regenerative design, innovation, and systems change in an organisational context is transformative rather than (predominantly) incremental in character, and we can therefore assume that the associated challenges overlap extensively with well-recognised disruptive (or radical) innovation barriers. Assink's (2006) conceptual model is highly relevant as it identifies five sets of barriers companies face when seeking to enhance their disruptive innovation capabilities: (1) innovation adoption, (2) mindsets, (3) risks, (4) infrastructure and (5) nascent challenges. Scholars note that adopting disruptive innovation is a significant challenge for organisations because it can oversimplify complex matters, and progress can remain limited due to time and funding constraints (Dorst, 2010; Nussbaum, 2011). Moreover, it is particularly challenging for companies to shift their mindsets and *unlearn outdated paradigms* to dispense with preconceptions that block disruptive innovation (Assink, 2006; Carlgren et al., 2016; Ahuja & Lampert, 2001). Also, since firms inhabit and depend on broader systems, supply chains, stakeholder groups and audiences, any dramatic business reorientations triggered by disruptive innovation – especially in the case of relatively established companies – require the careful management of such external systems, stakeholders and audiences as well (e.g. McDonald & Gao 2019). Risk-related barriers can lead to a strong focus on short-term solutions to minimise immediate financial risks (Neely & Hii, 1999; Assink, 2006). Infrastructure and nascent barriers include a lack of competencies in relation to an emerging, innovative domain, as well as difficulties with persuading stakeholders and clients of the value of a novel, poorly understood innovative product or service. Although new regenerative and circular material innovation startups may find strategic reorientations easier to perform than established companies, their disruptive innovation efforts depend on wider systems, stakeholder relations, supply chains and audiences.

Second, another set of barriers we anticipate emanates from the complexity of natural (living) systems and how human activities interact and intertwine with such systems. Understanding how to consciously, ethically and creatively collaborate with living organisms and ecosystems to generate novel materials and address problems such as the climate crisis will likely be challenging for most companies (Wahl, 2006). The need to develop a deep, nuanced and dynamic understanding of these issues, including the specific biological and ecological context of a given project and its integration possibilities with living systems (Reed, 2007b), counts as a distinctive regeneration challenge beyond the general barriers associated with disruptive innovation. To meet this challenge, it is clear that companies will need to urgently develop new competencies and diverse sources of knowledge based on multi- and transdisciplinary approaches, not only on biology or ecology.

Third, although scholars and practitioners have extensively discussed the shift from sustainability to regeneration in design along with general implementation challenges (Reed, 2007a; Wahl, 2016), less attention has been paid to dissecting *industry-specific barriers*. We anticipate the material science companies chosen for our study to face challenges and barriers that differ markedly from those faced by regenerative companies in sectors such as agriculture, food and the built environment. The underlying 'general' barrier herein is the difficulty of transcending and adapting (widely diffused but often unhelpfully broad) high-level regenerative principles to the realities and specificities of each industry, material, product category and so on. As industry-specific case studies, insights, and analyses accumulate, this barrier will likely be progressively alleviated.

4 Methods

This section briefly outlines our methodological approach and the specific methods applied. Implementing regenerative principles in material science companies is a challenging process requiring a holistic approach. As this approach is a nascent field, it motivates a qualitative research design (Edmonson & McManus, 2007). Therefore, this study employs qualitative data analysis based on an interpretivism philosophy, carrying out an inductive, exploratory interview-based study to address *empirical gaps* in the existing literature responding to the following research questions:

> ($\mathcal{RQ}$1) *What are the obstacles and prerequisites to implementing regenerative principles in the ideation phase (or the material design phase), and how is this new approach changing how companies innovate?*
>
> ($\mathcal{RQ}$2) *What challenges do organisations face when translating regenerative ideas into tangible materials and introducing them to the market?*

Primary data was collected through a semi-structured interview-based study guided by the research questions using purposive sampling to gather information-rich responses (Saunders & Thornhill, 2019; Leavy, 2017). The study is inductive and employs a cross-sectional time horizon and a mono-method qualitative approach to investigate organisations (Eisenhardt, 1989; Saunders & Thornhill, 2019). The interviews revolved around the participant's approach to problem definition, material solution discovery to tackle the identified issue, utilisation of regeneration, and the obstacles and prospects required to implement it during the conceptualisation phase. Additionally, the key steps required for commercialising the innovation and barriers encountered in meeting market demands were also discussed (Appendix 1). These focus areas were used to iteratively develop the researchers' understanding of the required changes and challenges companies face when implementing regenerative principles in ideation and implementation phases, gathering real-life examples and thought processes.

The study builds on a sample of 12 participants from the textile manufacturing, biotechnology, and packaging industries in managerial or research and development (R&D) roles who innovate naturally grown materials or circular solutions that replace extractive materials, investigating their perceptions of applying regenerative principles (Table 1). Participants were recruited through acquaintances, from networking events for material innovation, and with snowball sampling by asking at the close of each interview for suggestions of other potential interview candidates. The organisations involved ranged from early-stage proof-of-concept to industrial manufacturing, operating for an average of four years. The semi-structured and open interviews, lasting between 30 to 40 minutes, were conducted online and audio-recorded with the participants' permission and under confidentiality, following the UAL Code of Practice on Research Ethics (UAL, 2020) and transcribed verbatim (Saunders & Thornhill, 2019). This research approach offers a multi-level insight into participants' experiences, providing valuable empirical evidence for future studies in this field.

Table 1. Overview of Study Participants

Participants	Industry	Position	Years in Industry
P1	Textile Manufacturing	COO	4
P2	Biotechnology Research, Packaging	Sustainability Strategist	5
P3	Sporting Goods Manufacturing	CTO & Material Scientist	10
P4	Textile Manufacturing	Regenerative Strategist	2
P5	Packaging and Containers Manufacturing	CEO	9
P6	Biotechnology Research	COO	3
P7	Textile Manufacturing	CTO	10
P8	Textile Manufacturing	Senior Design Engineer	2
P9	Biotechnology Research	Founder & Creative Director	4
P10	Biotechnology Research	Co-Founder & CEO	7
P11	Biotechnology Research	Co-Founder & CEO	6
P12	Biotechnology Research	Lead Mycologist	3

The data was analysed based on in vivo coding for the first-cycle coding of the small-scale studies to understand participants' experiences in material innovation and regeneration (Stringer, 2020; Saldaña, 2021), followed by thematic analysis and three rounds of iteration to develop more abstract codes. Patterns emerged through the iterative synthesis and analysis of developed codes from all 12 transcripts, which were formulated into overarching categories and subcategories (Saldaña, 2021) (Appendix 2). However, the study recognises the potential intrusiveness of the researcher and the possibility of informant errors (Creswell & Creswell, 2017). Additionally, the study only speculates what participants think while operating, which might obscure their motivations and lower their in-depth understanding of their skill sets and techniques (Kimbell, 2011; Johansson-Sköldberg et al., 2013; Carlgren et al., 2016). Therefore, it acknowledges the need for further empirical research on adopting regenerative principles, including more extensive, longitudinal ethnographic studies and real-time experiences, to comprehensively understand industry-specific challenges.

5 Applying regenerative principles to material design and innovation: Perceived challenges

The field of material science has made notable strides in creating innovative materials, employing a diverse range of resources shared by the participants, such as fungi, microorganisms, collagen, seaweed, crops, cork, and non-toxic polymers that can be recycled. However, this study indicates that despite this progress, companies in this industry require substantial support to scale up their innovations for implementation in industrial settings. It identifies seven key themes that address the challenges faced by the interviewees when attempting to bring their innovative ideas to market (Figure 1).

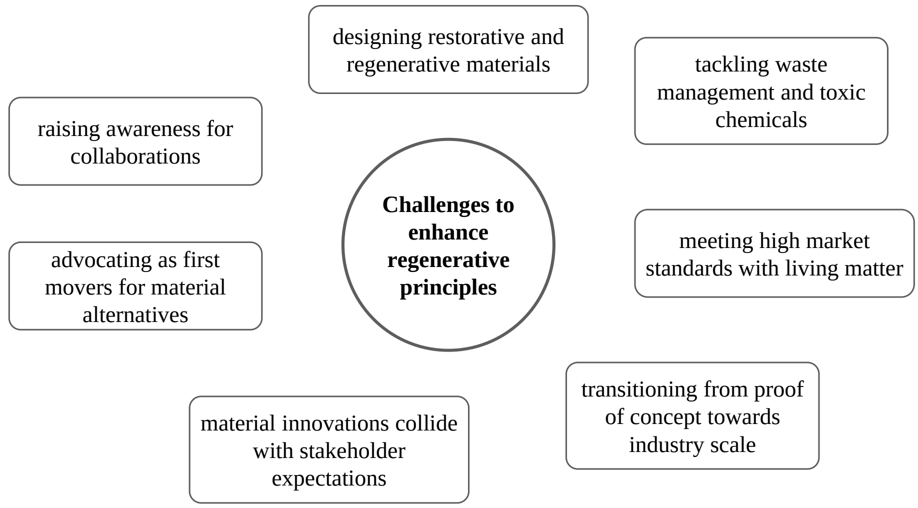

Figure 1. Overview of Challenges to Enhance Regenerative Principles.

Challenge 1: Designing restorative and regenerative materials

This study delves into the perceptions and implementation of the regenerative paradigm in material design practices. To explore participants' understanding of regenerative principles, the first research question (RQ-1) investigates how they conceptualised the problem of achieving a regenerative state and identified obstacles: What are the obstacles and prerequisites to implementing regenerative principles in the ideation phase (or the material design phase), and how is this new approach changing how companies innovate? The study identifies the main themes of sustainability, regeneration, regenerative agriculture, restoration, biodiversity, and ecosystem health. Notably, participants expressed their concern regarding the loss of meaning of the concept of sustainability, stating that it merely aims to cause less environmental harm without adding any value. They argue that a system that cannot evolve should not be sustained, and its existence should be questioned (1,9,11). On the other hand, regeneration is perceived as a more holistic approach involving ecosystem restoration and regeneration (1,8,9,10). However, some participants expressed difficulty innovating materials that positively impact ecosystems while addressing the overall plastic waste problem (2,4,7).

Only half of the interview participants explicitly prioritised regeneration, while the rest focused on building a closed-loop system with biodegradable materials. They are either building recycling systems or existing infrastructures for easier implementation, aiming to keep the products' circularity as long as possible before returning them to Earth (2,3,7,8,12). Some companies have turned to regenerative agriculture as a critical application to enhance ecosystem health and encourage farmers to restore their soil biodiversity, prioritising social and environmental well-being (1,2,4,5,7). Such companies have applied crop rotation, avoided water-intensive mono-crops to retain soil health, improved yields without fertilisers, and enhanced resilience to extreme weather with increased soil carbon stocks and water-holding capacities (1,4,9). However, it must be noted that solutions can only apply to the local and bioregional ecosystems and must be adapted to other geographic areas. Therefore, monitoring and maintaining these activities becomes pivotal to fully activating the regenerative potential long-term (4). Overall, managers face the design challenge of establishing new benchmarks for regenerative materials that restore the environment within an economic system that significantly contributes to plastic pollution.

Challenge 2: Tackling waste management and removing toxic chemicals

Material science faces a multifaceted challenge in pursuing sustainable alternatives. An industry-wide comprehensive approach is needed to address raw material sourcing and reducing emissions (1,4,10). Nevertheless, the geographic constraints and the need for toxic chemicals in processing rubber, cotton and leather have necessitated innovative solutions (4,6,7,8). Therefore, participants have concentrated on eliminating plastic waste and creating material alternatives that add value holistically and eliminate toxic petrochemicals (1,2,3,5,9,11,12). Most are sourcing materials locally or continentally (1,2,3,4,6,7,8,9,10,11,12) and mitigate the negative impact of products made of multi-fibre material, which are generally incinerated at the end of their lifecycle, as they cannot be recycled (2,3,9). Other roadblocks to enhancing regeneration include the overall consumption of resources and the need to shift mindsets towards consuming less (1,5,9). Managers must balance a holistic approach to sourcing raw materials, reducing emissions, eliminating waste, material alternatives, and resource consumption while promoting regeneration and shifting mindsets.

Challenge 3: Meeting high market standards with living matter

The study of the second research question (RQ-2) examines the challenges faced in meeting market requirements and convincing companies to adopt material alternatives, from ideation to industrial-scale implementation: What challenges do organisations face when translating regenerative ideas into tangible materials and introducing them to the market? The analysis reveals several themes, including R&D, empathising with organisms, material performance, constant feedback loops, scaling, lengthy processes, supply chain design, pricing, and data collection. Enhancing mechanical material strength, quality, and durability is crucial to achieving competitive materials that meet industry standards (3,4,6). As such, participants focus on R&D and work in creative, technical, and multidisciplinary teams to develop products that meet customer expectations. The company's role is to push the boundaries of how materials are perceived and find creative solutions (9,12). However, this lengthy process requires dealing with the uncertainty of trialling materials and learning through experience, ranging from several months to a few years (9,10,12).

To design sustainable materials, one must empathise with organisms, understand their behaviours in different environments, and build new tools to enhance their growth (8,9,10,12). Some participants have had a strong relationship and emotional awareness of nature from an early age (7,10,11). Others felt a relational responsibility to shift towards regenerative practices when learning about the environmental impact of plastic pollution during their studies (1,8,9), sharing that they were "shocked at how we were being taught something that we should transition away from" (9).

Prototyping begins with constant feedback loops from all stakeholders to learn more about unsustainable materials and to find customised alternatives (1,3,7,10,11,12). Companies must then prove the positive material impact while selling it to their (potential) B2B customers and tackling price parity, as new alternatives are more expensive than conventional materials at the beginning (4,8). Therefore, companies depend on funding to scale up first, set up their supply chains, and increase order quantities, which requires convincing B2B customers to buy (2,4,5,7,11). Here, managers are tasked with producing new materials that meet industry standards while navigating the unique properties of living organisms and the associated scalability obstacles to competing with established materials, such as plastics.

Challenge 4: Transitioning from proof of concept towards industry scale

Several challenges exist in transitioning from proof of concept to industry scale to simultaneously meet stakeholder demands and provide closed-loop systems (1,3,6,9,10,12). Data availability and collection are necessary to comprehend how much is compensated with the new material (1,3,4,6). However, the likelihood of the material's lifetime and performance over decades can only be theorised (1,3,6,9,10,12). Compounding this is the need for a full lifecycle assessment of the material, which tends to only be in the middle of the supply chain (1). As such, scale-up engineers are needed to design new factories to increase the output of new materials and thereby reduce their cost through economies of scale (1,4,11,12).

The current approach to introducing material alternatives into supply chains relies heavily on scaling up before partnering with larger manufacturing facilities (5,9,10). This poses a significant challenge, as convincing more prominent players to adopt new materials and processes can be difficult. Instead, a more practical approach would involve multiple big players taking the first step to advocate for these alternatives and increase market demand (3,6,11). However, this requires a shift in mindset regarding the role of businesses in promoting regeneration and balancing growth with ethical considerations within a capitalist system (1,11).

Securing funding for regenerative initiatives can also be challenging. Many material science companies rely on non-dilutive funding to support their hardware, material, or R&D initiatives, mainly when factories are less available or end-of-life pathways and recycling are the focus. However, convincing stakeholders to invest in regenerative solutions at the prototype stage is only possible once substantial environmental and social impact measurements are presented (2,5,9,10). To address this issue, rigorous research should be conducted to support the benefits of regeneration and encourage investment in the early stages (1,3,6,9,10,12). Managers face a range of challenges, such as obtaining funding for regenerative materials and establishing scalable supply chains. They must also navigate ethical considerations while balancing growth within a capitalist system.

Challenge 5: Material innovations collide with stakeholder expectations

Companies' implementation of material innovations presents significant challenges, which require process-based thinking and realistic goals within the fast-paced industry timelines while balancing the lengthy development of natural materials (8,10,12). However, when working with multinational companies, the implementation process can be slowed down due to various protocols, intellectual property protections, and approval processes (2,9). Additionally, the development and production of materials often take considerable time to meet each other, with a conventional production and disruptive design approach pushing the boundaries of what is possible (9,12). Despite the ecological benefits of new materials, B2B customers are hesitant to invest in them due to their higher costs and the longer time required to realise these benefits (1,3,7,8,12). Achieving price parity often requires increased order quantities, which may not be feasible for many material science companies. However, B2B customers are unwilling to pay more (2,4,5,7,11).

Additionally, traditional views on material use and performance have been shaped by plastics, resulting in B2B customers being reluctant to embrace new, natural alternatives (3,4,6,8). Natural materials often struggle to meet industry standards regarding petroleum-based materials' performance, quality, and aesthetics, leading to customer frustration (1,6,7,11,12). To overcome this obstacle, new definitions and parameters are needed to validate the material alternatives and provide proof of concept. Some participants believe that adopting these solutions is easy and that the market is ready as long as the end-consumer experience and usability of the product are maintained (2,3,8). In general, implementing material innovations presents significant design challenges for managers, including meeting industry standards, overcoming customer reluctance, and balancing the development of natural materials with the fast-paced industry timelines.

Challenge 6: Advocating as first movers for material alternatives

Collaboration, legislation, funding, market demand, advocacy, customer education, and knowledge transfer are among the common themes reported by interviewees concerning the development of circular or regenerative practices. Obstacles have been encountered in empowering industries to interact with new materials (1,8,10). Therefore, participants have become thought leaders to develop new paths and answer pertinent questions, but collaboration among stakeholders is crucial to applying system thinking and pushing boundaries towards circular and regenerative practices (1,3,5,6). Despite this, legislative bodies have responded slowly, with policies focusing only on carbon neutrality and technological innovation, leading to some frustrations (2,3,7). Regulations must address the new cluster of material innovations and how to handle them at the end of life (4,5,6,7). Thus far, legislation is currently being developed to address the harmful effects of petroleum-based products on human health and the environment (3,5).

Access to non-dilutive funding in the early stages of innovation is crucial. However, fewer grants are available to support hardware, material, or R&D with a factory and instead prioritise end-of-life pathways and recycling (2,5,9,10). Hence, budget constraints can make it difficult for early-stage businesses to utilise large-scale machinery costing thousands of pounds, making stakeholders wary of risking their equipment for new materials (9). Managers must collaborate with stakeholders, navigate and advocate during slow legislative response, secure funding, and develop end-of-life pathways to implement circular or regenerative practices.

Challenge 7: Raising awareness for collaboration

Regenerative innovation is hindered by B2B customers' reluctance to allocate resources and time towards incorporating new materials into their supply chains (10). This lack of initiative is a critical issue as B2B customers need to be educated about the environmental impact of products since many multinational companies lack the necessary knowledge to make informed decisions (2,11). Unfortunately, people tend to overlook the materials and organisms involved. They are accustomed to mass-produced items that lack unique shapes (2,11). To shift B2B customers' mindset towards net-positive materials and decentralise new alternatives, participants must convince them of the regenerative benefits of novel material properties and their end-of-life pathways (2,4,5,7). However, B2B customers prefer short-term success through successful marketing stories rather than knowing each supply chain step, which poses a challenge and maintains existing structures (1,6,7). Research participants feel that B2B customers want to sell the *name* of each given material (e.g. fungi) so as to be more recognisable in the market, as these can have symbolic and commercial value for them, rather than prioritising performance and environmental impact (3,4,11).

To overcome this challenge, fostering strong knowledge exchange activities with experts and throughout the value chain in relation to the B2B customer is essential (1,4,10). Additionally, marketing efforts are crucial in contextualising, narrating, and simplifying R&D and material benefits for each B2B customer and end-consumer. Nonetheless, the challenge in the long term is to address B2B customers who do not prioritise sustainability or regeneration (5). Engaging in an ongoing dialogue with farmers and cultivation communities to educate them about soil health and restore the biodiversity of their lands is also crucial (1,4,7). These collaborative efforts require early engagement, co-creation with nature, and finding synergies with different groups and interests that tackle the problem differently (1,9,10). To promote circular and regenerative materials, managers must address B2B customers' hesitancy to invest resources and time in adopting new materials, educate them about the environmental impact of products, and convince them of the long-term benefits of new material properties while also contextualising and simplifying R&D and material benefits for each B2B customer.

6 Discussion

The study discusses the challenges and requirements faced by material science companies that seek to integrate regenerative principles in material design and scaling. It contributes to broader sustainability transitions research, regenerative framework debates, and to emerging research on regenerative material innovation. Taking a multidimensional view, it provides empirical insights into overcoming innovation adoption, mindset, risk, nascent and infrastructure barriers (Assink, 2006) that material innovators encounter when implementing regenerative principles (Appendix 2). The present section critically reflects on these insights and links them to the initial research questions as well as existing literature. It highlights two main takeaways relating to developing competencies for whole-system thinking as well as shifts in mindset and collaboration among stakeholders during the scaling process. We briefly consider how the study participants are tackling each of these challenges.

Overcoming mindset barriers and realising design for regeneration

Our first research question focused on identifying the requirements for overcoming challenges in relation to incorporating regenerative principles in the ideation phase or the innovation journey. It has been observed that human-centric or human-only design approaches are insufficient in addressing systemic issues and promoting regenerative principles in material innovation. This is primarily due to the human/nature dualism entrenched in Western design, which can be considered a root cause of ecological problems (Wahl, 2016; Whitmee et al., 2015; Mang & Reed, 2011; Orr, 1994). To overcome this, companies must adopt a regenerative mindset towards material resources and collaborate with nature (Ericson et al., 2014; Wamsler et al., 2018; Mang & Reed, 2012). However, a lack of institutional support and incentives hinders the implementation of regeneration paradigms, leading to temporary solutions (Coyne, 2005). To overcome mindset barriers, managers must therefore comprehensively evaluate the impact of each stage of the supply chain on affected ecosystems and work in partnership with nature (Tansley, 1935; Mang, 2009; Reed, 2007b). Interview participants highlight that to shift B2B customers' mindsets towards net-positive alternatives and promote the regenerative benefits of novel material properties and their end-of-life pathways, managers must push the boundaries of material perception, embrace uncertainty, and apply new competencies (2,5,9,10). According to Brown (1998), modifying the mental models of a corporation and its underlying business models is an immensely challenging task. Some suggest that empathising with organisms, comprehending their actions, and creating new tools to boost their development are critical for designing regenerative materials (Toivonen et al., 2022; Wissinger, 2023). Furthermore, addressing emotional attachment to conventional materials or reluctance to transition towards regenerative practices requires rigorous research into the benefits of regeneration and investment in the early stages.

To transform the current degenerative economic system and societal values, companies must take a collaborative, holistic approach towards environmental stewardship and address power dynamics, build local inclusive knowledge, and value different knowledge systems (Hickel, 2020; Moriggi et al., 2020; Bendoly, 2014; Williams, 2016; Chronéer & Backlund, 2015; du Plessis & Cole, 2011). Unfortunately, developing the new knowledge needed to support these shifts often lacks systemic thinking and is fragmented in feasibility (Fazey et al., 2020). The Three Horizons model can provide a pathway to transformative change, but its implementation on a larger scale requires a significant shift in values and ethics (Sharpe et al., 2016). Whole-system thinking, which is a transdisciplinary approach, offers a way to understand the interconnectedness of the system and its ecological hierarchies across scales and how they relate to human aspirations to improve the capacities of social and environmental processes to identify critical leverage points (Wahl, 2016;

Meadows, 1999; Lyle, 1984). Early-stage businesses that tackle waste management issues through circularity and regeneration paradigms should aim to improve the capacities of whole systems rather than just finding solutions for current challenges (Mang & Haggard, 2016). Thus, companies must critically comprehend the master pattern of place, translate patterns into (design) guidelines, and establish ongoing feedback to foster mutual understanding and caring (Reed, 2007b). Additionally, they must find approaches to partner with nature, restore and create a flourishing ecosystem, and support the co-evolution of the built environment, cultural practices, and natural systems (Mang & Haggard, 2016; Reed, 2007a). Furthermore, taking a collaborative, holistic approach towards rethinking economic systems and societal values to drive systemic transformations, build resilience, and navigate the complexities of living systems to address ecological problems (du Plessis & Cole, 2011; Bendoly, 2014; Williams, 2016; Chronéer & Backlund, 2015). These approaches foster interconnected living systems awareness, leading to a paradigm shift and positive social and environmental outcomes that transition towards 'biobecoming' (Mang & Reed, 2011, p. 15).

Challenges of adopting regenerative materials at scale

Implementing regeneration in material design requires collaboration among a complex network of stakeholders, including those in legislation, funding, manufacturing, business, media, education, and the general public. This was highlighted by the interview findings for the second research question that observed what obstacles companies encounter while transforming regenerative principles into products and entering the market. However, large corporations are hesitant to adopt innovative materials and processes due to an insufficient understanding of living matter and its intricate ecosystems (2,4,5,7,11). Additionally, larger companies that material science startups aim to target may find product sales margins inadequate due to their higher cost structure (Loutfy & Belkhir, 2001). This resistance is further exacerbated by a lack of environmental knowledge and hesitation to pay more for new materials still in the early stages of development (Assink, 2006; Leifer et al., 2001). Overall, numerous companies lack the structure or culture to embrace innovative ideas, identify significant shifts in the market, respond promptly to changing market conditions, or drive market changes themselves (Markides, 1999). Funding schemes and support with material experimentations and scaling of transformative approaches play a critical role in advancing the regenerative paradigm (Irwin et al., 2018; Waddell, 2016). However, the need to forecast financial gains from investments in innovative ideas can impede the progress of their disruption (Harper & Becker, 2004).

Moreover, stakeholders require feasibility proof before investing in regenerative materials, and material science companies must focus on tangible research findings and data to build trust (1,3,4,6). This results from many large corporations struggling to balance maintaining consistency for incremental innovation with promoting flexibility and experimentation for radical innovation, such as regenerative materials (Cosier & Hughes, 2001; Tushman & O'Reilly, 2002; Sharma, 1999). According to the interviews, early-stage companies must uphold in constant feedback loops with stakeholders and research regeneration impacts to overcome infrastructure and nascent barriers (1,3,7,10,11,12). Additionally, they should collaborate with or become system builders to invent new materials and determine the best way to produce them in large-scale factories to prove their positive material impact and tackle price parity (4,8).

Pre-revenue material science companies often rely on funding to build larger teams and infrastructure to deliver such data and understand how their impact compensates for emissions, but few investors focus on materials or hardware (2,5,9,10). Engaging stakeholders early on and collaborating with larger companies to promote whole systems thinking can help participants unlock their regenerative potential to compete in a growth economy that favours profit (Mang &

Reed, 2012). The conventional theories of design and innovation management may not suffice when overcoming the obstacles to innovation in material science companies. These entities must constantly innovate and assume the role of system builders, educators, storytellers, and advocates to successfully implement their materials (Muñoz & Branzei, 2021).

The new empirical insights show that it is imperative to establish a regulatory framework first that incentivises companies to develop regenerative solutions and introduces novel standards for organic materials and living matter that facilitate their entry into the market. This would require legislative action that shifts the focus of investment portfolios and grants, supporting early-stage companies to scale from proof of concept towards production at scale. Such measures would help address the critical gaps between regenerative principles and their implementation and promote holistic symbiotic solutions (1,3,7,8,12). However, innovation management that oversimplifies complex systemic problems and eschews continuous feedback loops of processes due to time and funding constraints can lead to unrealistic recommendations and hamper the discovery of novel solutions. This approach often lacks critical reflection and fails to addressing power imbalances and systemic inequalities (Dorst, 2010; Nussbaum, 2011; Neely & Hii, 1999; Assink, 2006). Consequently, the failure of regenerative projects can often be attributed to their narrow focus on specific elements or problems without considering their systemic connections (Mang & Reed, 2011).

7 Managerial Implications

This paper provides a comprehensive guide for managers on effectively applying regenerative principles to promote innovation and regeneration in material design (Table 2). It draws on regenerative principles and innovation management to recommend a series of interrelated steps managers can take to activate regenerative potentials. This includes scrutinising the linear system and its impacts on the life cycle stages of materials, identifying problems that can produce positive outcomes, and finding synergies between the social and ecological dimensions of an affected area. To develop a regenerative mindset, companies must define their role, evaluate available resources, build a multidisciplinary team, and think symbiotically when acquiring partners and impacting ecosystems to generate multiple long-term solutions. Managers must prioritise regenerative thinking, identify systems-level intervention points, find materials that encourage regeneration, determine who and what benefits from the solution, and establish a narrative between themselves and the place while manifesting their motivations.

The study emphasises the importance of early engagement with local and bioregional stakeholders and reliance on nature to guide the innovation process. Practical communication skills are equally essential, and feedback loops with multiple stakeholders are crucial to ensure continuous improvement. Companies must take responsibility for the impact of their work by designing regenerative systems, testing and prototyping solutions, and collecting data on the entire lifecycle of their materials. In conclusion, the study offers managers a roadmap for implementing regenerative principles in material design that can promote innovation and regeneration.

Table 2. Overview of Managerial Implications

Innovation Barriers	Challenges	Implications
Adoption	Incorporating regenerative principles into design to create innovative materials that combat plastic waste and positively impact ecosystems.	Examine linear systems in a material's life cycle, pinpoint issues, and identify an intervention point to enhance the human-affected area relationship.
Mindset	Overcoming mass consumption habits, eliminating toxic petrochemicals with material alternatives, and addressing waste management.	Develop a regenerative mindset that prioritises symbiotic interactions with the Earth. Identify intervention points, determine who/what benefits, establish a narrative with the place, and manifest motivations.
Risk	Balancing industry timelines and standards with the pace of living matters while accommodating demand for alternative materials priced like traditional ones and addressing manufacturers' environmental responsibility.	Advocate for your field to advance research and legislation by contextualising the problem and establishing feedback channels to address concerns and explain your solution in a way anyone can understand.
Nascent	B2B customers prioritise short-term campaigns over long-term impact, and no apparent material innovation and disposal regulations exist.	Define your role in the system, evaluate resources, build a team, engage in an ongoing dialogue with stakeholders early on and educate B2B customers on material lifecycles.
Infrastructure	Collecting data and securing funding to transition from proof of concept to industry scale while measuring emission compensation.	Design systems with nature as a guide, prototype solutions, collect lifecycle data and be responsible for the impact of your work.

Limitations and future directions

Innovation in material design is essential for advancing the field. However, regenerative approaches have limitations, as ingrained on past ideologies can pose significant challenges and require systemic change. Shifting to natural materials may solve one problem but can create new environmental problems. To adopt regenerative principles, organisations must deeply understand them and integrate them into all business functions. This requires re-evaluating mindsets and interactions to align with regenerative practices. The research acknowledges the narrow Western- or Euro-American-centric positions to design and regeneration in a context where Indigenous people steward 80 percent of the planet's biodiversity (Hickel, 2020). Hence, scholars must establish a comprehensive ontology of human nature (Rosiek et al., 2020). The ideation phase of design is crucial to assessing the environmental impact and synthesising concepts to prioritise human and planetary health is imperative (Lang-Koetz et al., 2008; Maxwell & Van der Vorst, 2003). Future research should encompass ethnographic studies of material science companies, regenerative business models (Konietzko et al., 2023), cultural studies (Wahl, 2016), material experience research (Karana et al., 2015), material perception (Soper, 2014), collaborative workspaces (Toivonen et al., 2022; Leminen et al., 2020) and Indigenous knowledge. Furthermore, a universal and measurable sense of when one becomes regenerative requires tools that offer customisation and parametric simulations (Ichioka & Pawlyn, 2021).

One possible avenue for future research of this paper is to investigate the interdependencies and relationships among the seven challenges discovered, assisting managers in understanding their dynamic nature. This could guide them in identifying the required steps to adopt regenerative principles in their companies' innovation processes. Additionally, the study could explore how factors such as scaling and achieving a measurable impact influence these needed steps. Another potential research avenue is to explore how the findings of this study could be applied to inform future policies that facilitate the adoption of regeneration methods and establish industry-wide standards.

8 Conclusion

This study delves into the process of implementing regenerative principles in material science companies. It sheds light on the gaps between regenerative principles and innovation management practices and offers insights into innovation adoption, mindset, risk, nascent and infrastructure barriers. Companies must tackle seven key challenges, including waste management, stakeholder expectations, and collaboration, to adopt regenerative principles and innovate processes to integrate them. The study provides vital managerial implications for managers and scholars seeking to innovate regenerative materials and positively impact their organisations. Adopting a more holistic approach that considers multidimensional systems thinking is crucial in innovation management to foster the design of (new) materials which support their ecological systems. However, achieving truly regenerative innovation requires a systemic shift and a re-evaluation of mindsets and interactions to reduce material impact within planetary boundaries and support the flourishing of 'all life for all time' (Ichioka & Pawlyn, 2021).

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9 References

Ahuja, G., & Morris Lampert, C. (2001). Entrepreneurship in the large corporation: A longitudinal study of how established firms create breakthrough inventions. *Strategic management journal*, *22*(6-7), 521-543.

Albrecht, G. A. (2019). *Earth emotions: New words for a new world*. Cornell University Press.

Assink, M. (2006). Inhibitors of disruptive innovation capability: a conceptual model. *Management*, *9*(2), 215-233.

Bacon, F. (1855). *The Novum Organon; Or, A True Guide to the Interpretation of Nature*. The University Press.

Barbier, E. B. (2005). *Natural resources and economic development*. Cambridge University Press.

Barile, S., & Saviano, M. (2018). Complexity and sustainability in management: insights from a systems perspective. *Social dynamics in a systems perspective*, 39-63.

Bendoly, E. (2014). System dynamics understanding in projects: Information sharing, psychological safety, and performance effects. *Production and operations management, 23*(8), 1352-1369.

Bowen, F. E., Bansal, P., & Slawinski, N. (2018). Scale matters: The scale of environmental issues in corporate collective actions. *Strategic Management Journal*, *39*(5), 1411-1436.

Brown, J. S. (1998). Seeing differently: a role for pioneering research. *Research-Technology Management*, *41*(3), 24-33.

Brundtland, G. H. (1987). Our common future—Call for action. *Environmental conservation*, *14*(4), 291-294.

Buchanan, R. (1992). Wicked problems in design thinking. *Design issues*, *8*(2), 5-21.

Capra, F. (1996). *The web of life: A new synthesis of mind and matter* (p. 336). London: Flamingo.

Carlgren, L., Elmquist, M., & Rauth, I. (2016). The challenges of using design thinking in industry–experiences from five large firms. *Creativity and Innovation Management*, *25*(3), 344-362.

Chronéer, D., & Backlund, F. (2015). A holistic view on learning in project-based organizations. *Project Management Journal, 46*(3), 61-74.

Circle Economy. (2023). *The circularity gap report 2023*. Amsterdam: Circle Economy, pp. 1-64, Rep.

Cole, R. J. (2012). Regenerative design and development: current theory and practice. *Building Research & Information*, *40*(1), 1-6.

Cosier, G., & Hughes, P. M. (2001). The problem with disruption. *BT Technology Journal*, *19*(4), 9-14.

Coyne, R. (2005). Wicked problems revisited. *Design studies*, *26*(1), 5-17.

Creswell, J. W., & Creswell, J. D. (2017). *Research design: Qualitative, quantitative, and mixed methods approaches*. Sage publications.

Crossan, M. M., & Apaydin, M. (2010). A multi-dimensional framework of organizational innovation: A systematic review of the literature. *Journal of management studies*, *47*(6), 1154-1191.

Crutzen, P. J. (2002). Geology of mankind: the Anthropocene. *Nature*, *415*(23).

Daly, H. E., & Daly, H. E. (Eds.). (1973). *Toward a steady-state economy* (Vol. 18). San Francisco: WH Freeman.

Descartes, R. (2000). *Discourse on method and related writings*. Penguin.

Descola, P. (2013). *Beyond nature and culture*. University of Chicago Press.

Dorst, K. (2010). The nature of design thinking. In *Design thinking research symposium*. DAB Documents.

Du Plessis, C. (2012). Towards a regenerative paradigm for the built environment. *Building Research & Information*, *40*(1), 7-22.

Du Plessis, C., & Cole, R. J. (2011). Motivating change: shifting the paradigm. *Building Research & Information*, *39*(5), 436-449.

Edmondson, A. C., & McManus, S. E. (2007). Methodological fit in management field research. *Academy of management review, 32*(4), 1246-1264.

Ericson, T., Kjønstad, B. G., & Barstad, A. (2014). Mindfulness and sustainability. *Ecological Economics*, *104*, 73-79.

Farrier, D. (2020). *Footprints: In search of future fossils*. Farrar, Straus and Giroux.

Fazey, I., Schäpke, N., Caniglia, G., Hodgson, A., Kendrick, I., Lyon, C., ... & Saha, P. (2020). Transforming knowledge systems for life on Earth: Visions of future systems and how to get there. *Energy research & social science*, *70*, 101724.

Geissdoerfer, M., Bocken, N. M., & Hultink, E. J. (2016). Design thinking to enhance the sustainable business modelling process–A workshop based on a value mapping process. *Journal of Cleaner Production*, *135*, 1218-1232.

Geyer, R. (2020). Production, use, and fate of synthetic polymers. In *Plastic waste and recycling* (pp. 13-32). Academic Press.

Geyer, R., Jambeck, J. R., & Law, K. L. (2017). Production, use, and fate of all plastics ever made. *Science advances*, *3*(7), e1700782.

Gibbons, L. V. (2020). Regenerative—The new sustainable?. *Sustainability, 12*(13), 5483.

Gladwin, T. N., & Newburry, W. E. (1997). WHY IS THE NORTHERN ELITE MIND BIASED AGAINST COMMUNITY. *Environment, ethics, and behavior: The psychology of environmental valuation and degradation*, 234.

Gonera, A., & Pabst, R. (2019). The use of design thinking in transdisciplinary research and innovation consortia: challenges, enablers, and benefits. *Journal of Innovation Management*, *7*(3), 96-122.

Hahn, T., & Tampe, M. (2021). Strategies for regenerative business. *Strategic Organization*, *19*(3), 456-477.

Hamilton, L. A., & Feit, S. (2019). Plastic & climate: The hidden costs of a plastic planet.

Hansen, M. T., & Von Oetinger, B. (2001). Introducing T-shaped managers. Knowledge management's next generation. *Harvard Business Review, 79*(3), 106-16.

Haraway, D. J. (2015). Anthropocene, capitalocene, plantationocene, chthulucene: Making kin. *Environmental humanities*, *6*(1), 159-16.

Haraway, D. J. (2016). *Staying with the trouble: Making kin in the Chthulucene*. Duke University Press.

Harper, S. M., & Becker, S. W. (2004). On the leading edge of innovation: a comparative study of innovation practices. *Southern Business Review*, *29*(2), 1.

Heger, T., & Rohrbeck, R. (2012). Strategic foresight for collaborative exploration of new business fields. *Technological Forecasting and Social Change, 79*(5), 819-831.

Heikkurinen, P., Clegg, S., Pinnington, A. H., Nicolopoulou, K., & Alcaraz, J. M. (2021). Managing the Anthropocene: Relational agency and power to respect planetary boundaries. *Organization & Environment*, *34*(2), 267-286.

Hickel, J. (2020). *Less is more: How degrowth will save the world*. Random House.

Ichioka, S., & Pawlyn, M. (2021). *Flourish: Design Paradigms for Our Planetary Emergency*. Triarchy Press.

Irwin, E. G., Culligan, P. J., Fischer-Kowalski, M., Law, K. L., Murtugudde, R., & Pfirman, S. (2018). Bridging barriers to advance global sustainability. *Nature Sustainability*, *1*(7), 324-326.

Jackson, T. (2009). Prosperity without growth?: The transition to a sustainable economy.

Johansson-Sköldberg, U., Woodilla, J., & Çetinkaya, M. (2013). Design thinking: past, present and possible futures. *Creativity and innovation management*, *22*(2), 121-146.

Kanger, L., & Schot, J. (2019). Deep transitions: Theorizing the long-term patterns of socio-technical change. *Environmental Innovation and Societal Transitions, 32*, 7-21.

Karana, E., Barati, B., Rognoli, V., & Zeeuw Van Der Laan, A. (2015). Material driven design (MDD): A method to design for material experiences. *International journal of design*, *9*(2), 35-54

Kidd, C. V. (1992). The evolution of sustainability. *Journal of Agricultural and Environmental Ethics*, *5*, 1-26.

Kimbell, L., 2011. Rethinking design thinking: Part I. Design and culture, 3(3), pp.285-306.

Kock, A., Heising, W., & Gemünden, H. G. (2015). How ideation portfolio management influences front-end success. Journal of *Product Innovation Management, 32*(4), 539-555.

Konietzko, J., Das, A., & Bocken, N. (2023). Towards regenerative business models: A necessary shift? *Sustainable Production and Consumption*.

Lang-Koetz, C., Beucker, S., & Heubach, D. (2008). Estimating environmental impact in the early stages of the product innovation process. *Environmental Management Accounting for Cleaner Production*, 49-64.

Leavy, P. (Ed.). (2017). *Handbook of arts-based research*. Guilford Publications.

Leifer, R., O'Connor, G. C., & Rice, M. (2001). Implementing radical innovation in mature firms: The role of hubs. *Academy of Management Perspectives*, *15*(3), 102-113.

Lent, J. (2018). The Patterning Instinct: A Cultural History of Humanity's Search for Meaning. *Arkansas Tech University*.

Leminen, S., Nyström, A. G., & Westerlund, M. (2020). Change processes in open innovation networks–Exploring living labs. *Industrial Marketing Management*, *91*, 701-718.

Leslie, H. A., Van Velzen, M. J., Brandsma, S. H., Vethaak, A. D., Garcia-Vallejo, J. J., & Lamoree, M. H. (2022). Discovery and quantification of plastic particle pollution in human blood. *Environment International*, *163*, 107199.

Liedtka, J., & Ogilvie, T. (2011). *Designing for growth: A design thinking tool kit for managers*. Columbia University Press.

Ljungberg, L. Y. (2007). Materials selection and design for development of sustainable products. *Materials & Design*, *28*(2), 466-479.

Loutfy, R., & Belkhir, L. (2001). Managing innovation at Xerox. *Research-Technology Management*, *44*(4), 15-24.

Lyle, J. T. (1984). Designing human ecosystems. *Island Press*.

Malm, A. (2015). The Anthropocene Myth. *Jacobin Magazine*, *30*.

Mang, P., & Haggard, B. (2016). *Regenerative development and design: a framework for evolving sustainability*. Wiley.

Mang, P., & Reed, B. (2020). Regenerative development and design. *Sustainable built environments*, 115-141.

Manzini, E. (2006). Design, ethics and sustainability. *Guidelines for a Transition Phase. University of Art and Design Helsinki (June)*, 9-15.

Markides, C. C. (1999). A dynamic view of strategy. *Sloan Management Review*, *40*(3), 55-63.

Maxwell, D., & Van der Vorst, R. (2003). Developing sustainable products and services. *Journal of Cleaner production*, *11*(8), 883-895.

McAloone, T. C., & Bey, N. (2009). *Environmental improvement through product development: A guide*. Danish Environmental Protection Agency.

McDonald, R., & Gao, C. (2019). Pivoting isn't enough? Managing strategic reorientation in new ventures. *Organization Science*, *30*(6), 1289-1318.

McDonough, W., & Braungart, M. (2002). Design for the triple top line: new tools for sustainable commerce. *Corporate Environmental Strategy*, *9*(3), 251-258.

Meadows, D. H. (1999). Leverage points: Places to intervene in a system.

Meadows, D. H., Meadows, D. L., Randers, J., & Behrens, W. W. (2018). The limits to growth. In *Green planet blues* (pp. 25-29). Routledge.

Moriggi, A., Soini, K., Franklin, A., & Roep, D. (2020). A care-based approach to transformative change: ethically-informed practices, relational response-ability & emotional awareness. *Ethics, Policy & Environment*, *23*(3), 281-298.

Muñoz, P., & Branzei, O. (2021). Regenerative Organizations: Introduction to the Special Issue. *Organization & Environment*, *34*(4), 507-516

Napper, I. E., Davies, B. F., Clifford, H., Elvin, S., Koldewey, H. J., Mayewski, P. A., ... & Thompson, R. C. (2020). Reaching new heights in plastic pollution—preliminary findings of microplastics on Mount Everest. *One Earth*, *3*(5), 621-630.

Neely, A., & Hii, J. (1999). The innovative capacity of firms. Report commissioned by the Government Office for the East of England. *Center for Business Performance, Judge Institute of Management Studies, University of Cambridge, UK*.

Nussbaum, B. (2011). Failed experiment: User-centered design and the myth of innovation. *Interactions,* 18(5), 52-57.

O'Brien, K., El Khoury, A., Schafenacker, N., & Rosenfeld, J. (2019). Our entangled future: stories to empower quantum social change. *Karen O'Brien, Oslo, Norway.*

Orr, D. W. (1992). *Ecological literacy: Education and the transition to a postmodern world*. Suny Press.

Papanek, V. (1971). Design for the Real World: Human Ecology and Social Change. New York: Pantheon Books.

Peng, X., Chen, M., Chen, S., Dasgupta, S., Xu, H., Ta, K., ... & Bai, S. (2018). Microplastics contaminate the deepest part of the world's ocean. *Geochemical Perspectives Letters*, *9*(1), 1-5.

Perry-Smith, J. E., & Mannucci, P. V. (2017). From creativity to innovation: The social network drivers of the four phases of the idea journey. *Academy of management review*, *42*(1), 53-79.

Persson, L., Carney Almroth, B. M., Collins, C. D., Cornell, S., de Wit, C. A., Diamond, M. L., ... & Hauschild, M. Z. (2022). Outside the safe operating space of the planetary boundary for novel entities. *Environmental science & technology*, *56*(3), 1510-1521.

Politowicz, K., & Earley, R. (2009). Sustainability and Enterprise: Testing the Theories with Design. In *Creative Connexions Conference*.

Raworth, K. (2017). Doughnut economics: seven ways to think like a 21st-century economist. Chelsea Green Publishing.

Raygorodetsky, G. (2018). Indigenous peoples defend earth's biodiversity-but they're in danger. Retrieved March 6, 2023, from National Geographic website: https://www.nationalgeographic.com/environment/article/can-indigenous-land-stewardship-protect-biodiversity-

Reed, B. (2007, May). A Living systems approach to design. In *AIA National Convention May–Theme Keynote Address.*

Reed, B. (2007b). Shifting from 'Sustainability' to Regeneration. *Building Research and Information*, 35(6), 674-680.

Rees, W. E. (1995). Achieving sustainability: reform or transformation?. *Journal of planning literature*, *9*(4), 343-361.

Rittel, H. W., & Webber, M. M. (1973). Dilemmas in a general theory of planning. *Policy sciences*, *4*(2), 155-169.

Rockström, J., Steffen, W., Noone, K., Persson, Å., Chapin III, F. S., Lambin, E., ... & Foley, J. (2009). Planetary boundaries: exploring the safe operating space for humanity. *Ecology and society*, *14*(2).

Rodale, R. (1983). Breaking new ground: The search for a sustainable agriculture. *Futurist*, *17*(1), 15-20.

Rosiek, J. L., Snyder, J., & Pratt, S. L. (2020). The new materialisms and Indigenous theories of non-human agency: Making the case for respectful anti-colonial engagement. *Qualitative Inquiry*, *26*(3-4), 331-346.

Royal, T. A. C. (2005). *Exploring Indigenous Knowledge* (pp. 1–20). The Indigenous Knowledges Conference.

Saldaña, J. (2021). The coding manual for qualitative researchers. *The coding manual for qualitative researchers*, 1-440.

Sanders, E. B. N., & Stappers, P. J. (2008). Co-creation and the new landscapes of design. *Co-design*, *4*(1), 5-18.

Saunders, M., Lewis, P. and Thornhill, A. (2019) Research Methods for Business

Schiederig, T., Tietze, F., & Herstatt, C. (2012). Green innovation in technology and innovation management–an exploratory literature review. *R&d Management*, *42*(2), 180-192.

Seuront, L. (2018). Microplastic leachates impair behavioural vigilance and predator avoidance in a temperate intertidal gastropod. *Biology letters*, *14*(11), 20180453.

Shapira, H., Ketchie, A., & Nehe, M. (2017). The integration of design thinking and strategic sustainable development. *Journal of Cleaner Production*, *140*, 277-287.

Sharma, A. (1999). Central dilemmas of managing innovation in large firms. *California management review*, *41*(3), 146-164.

Sharpe, B., Hodgson, A., Leicester, G., Lyon, A., & Fazey, I. (2016). Three horizons: a pathways practice for transformation. *Ecology and Society*, *21*(2).

Soper, K. (2014). Alternative hedonism, cultural theory and the role of aesthetic revisioning Cultural Studies and Anti-Consumerism (pp. 59-79). Students. 8thEdn. Essex: Pearson Education (eBook available)

Tansley, A. G. (1935). The use and abuse of vegetational concepts and terms. *Ecology*, *16*(3), 284-307.

Tidd, J., & Bessant, J. R. (2020). *Managing innovation: integrating technological, market and organizational change*. John Wiley & Sons.

Toivonen, T., Hecker, M., Weiermann, L. (2022). Designing New Spaces of Creativity for the Regenerative City. University of the Arts London.

Tsing, A. L. (2015). The Mushroom at the End of the World. In *The Mushroom at the End of the World*. Princeton University Press.

Tushman, M. L., & O'Reilly III, C. A. (1996). Ambidextrous organizations: Managing evolutionary and revolutionary change. *California management review*, *38*(4), 8-29.

Tushman, M., & O'Reilly, C. A. (2002). *Winning through innovation: A practical guide to leading organizational change and renewal*. Harvard Business Press.

UAL, 2020. Code of Practice on Research Ethics. Internet. Available from: http://www.arts.ac.uk/media/arts/research/research-degrees/Code-of-Practice-on-Research-Ethics.pdf (Accessed: 30 November 2022).

Waddell, S. (2016). Societal change systems: a framework to address wicked problems. *The Journal of Applied Behavioral Science*, *52*(4), 422-449.

Wahl, D. C. (2016). *Designing regenerative cultures*. Triarchy Press.

Wahl, D. C. (2006). Design for human and planetary health: a transdisciplinary approach to sustainability. *Manag Nat Resour Sustain Dev Ecol Hazards*, *99*, 285.

Wamsler, C., Brossmann, J., Hendersson, H., Kristjansdottir, R., McDonald, C., & Scarampi, P. (2018). Mindfulness in sustainability science, practice, and teaching. *Sustainability science*, *13*, 143-162.

Whitmee, S., Haines, A., Beyrer, C., Boltz, F., Capon, A. G., de Souza Dias, B. F., ... & Yach, D. (2015). Safeguarding human health in the Anthropocene epoch: report of The Rockefeller Foundation–Lancet Commission on planetary health. *The lancet*, *386*(10007), 1973-2028.

Williams, T. (2016). Identifying success factors in construction projects: A case study. *Project management journal, 47*(1), 97-112.

Wissinger, Elizabeth. (2023). "Can Biodesign Fix Fashion?" Arts Imagining Communities to Come, Guayaquil, Ecuador, 8-11 November 2021. *Cumulus Association*.

Xu, Z., Zhang, Y., Lin, L., Wang, L., Sun, W., Liu, C., ... & Wang, Y. (2022). Toxic effects of microplastics in plants depend more by their surface functional groups than just accumulation contents. *Science of the Total Environment*, *833*, 155097.

10 Appendix

Appendix 1. Semi-Structured Interview Framework

Number	Theme	Main Interview Questions	Follow-Up Questions
RQ-1	Preamble	Briefly introduce yourself and your background in material science.	For how long have you been working in material science?
	Materials	What type(s) of material(s) do you work with?	What issues are you addressing with your innovation?
	Problem Ideation	Can you outline the journey of how you discovered and defined the problem you are addressing?	
	Obstacles	What does regeneration mean to you? What are the biggest challenges in implementing strategies that align with nature during the concept phase?	
	Prerequisites	Which aspects would have to change to realise the regenerative potentials in innovations? What are the biggest opportunities for realising regenerative potential?	
RQ-2	Implementation	Which main steps in the commercialisation phase are crucial for successfully launching your specific innovation?	
	Obstacles	What are the biggest challenges in meeting market requirements when commercialising a new product like yours?	

Appendix 2. Overview of Main Challenges to Applying Regeneration in Design

Number	Themes	Main challenges
RQ-1	Regeneration. Restoration. Biodiversity. Ecosystem health.	Implementing regenerative principles in design practices. Designing materials that positively impact spaces and address the plastic waste problem.
	Problem definition. Plastic pollution. Material impact. Human impact on the environment. Conventional materials. Conventional supply chains.	Addressing waste management and toxic chemicals such as disposable single-use plastics and identifying material alternatives to eliminate toxic petrochemicals. Tackling mindset barriers to overcome mass consumption.
RQ-2	R&D. Empathise with organisms. Material performance. Feedback loops. Scaling. Lengthy processes. Supply chain design. Pricing. Data collection.	Achieving durable and high-quality products that meet market standards while working with living matter. Natural materials require more time and space to evolve, posing a challenge for companies to balance fast-paced industry timelines and turnaround. Transitioning from proof of concept towards industry scale, reconciling that with the industry demand, and providing a closed-loop system. Manufacturers feel less accountable for the impact of their materials later in the supply chain and lack engagement. B2B customers are not yet using new materials, as they are more expensive than traditional materials and require larger orders and similar prices. Natural materials may only sometimes be able to meet the high industry standards in terms of petroleum-based materials' performance, quality, and aesthetics. Collecting data to understand how much negative impact is compensated.

Number	Themes	Main challenges
	Collaboration. Legislation. Funding. Market demand. Advocacy. Customer education. Knowledge transfer.	Early engagement, co-creation with nature, and finding synergies with different groups. Contextualising the problem and raising awareness for collaborations, and marketing the material benefits for each customer and the public. Compete with B2B customers that focus on short-term marketing stories promoting greenwashing rather than having a long-term impact. Lack of regulations that respond to new material innovations and their end-of-life pathways. New definitions and parameters are needed to validate the material alternative and prove its concept. Limited availability of non-dilutive funding for hardware, materials, or R&D with a factory has led to budget constraints and difficulty in utilising large-scale machinery. B2B customer education and knowledge transfer are necessary to raise awareness and create demand for new materials.

Biographies

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