External Research Report ER105 [2025]

Bio-materials for low-carbon built environment: Fostering the new good

Dr Emina Kristina Petrović, Maria Walker, Mike Murray, Dr Dermott McMeel, Derek Kawiti, and Max Young

Project LR16997

Victoria University of Wellington, funded by the Building Research Levy

Funded from the Building Research Levy

1222 Moonshine Rd, RD1, Porirua 5381

Private Bag 50 908, Porirua 5240
New Zealand

ISSN: 2423-0839

Bio-materials for low-carbon built environment: Fostering the new good

Dr Emina Kristina Petrović, Maria Walker, Mike Murray, Dr Dermott McMeel, Derek Kawiti, and Max Young

2025

BRANZ
Funded from the Building Research Levy

1897
VICTORIA UNIVERSITY OF WELLINGTON
TE HERENGA WAKA

AUT
TE WĀNANGA ARONUI O TĀMAKI MAKAU RAU

Acknowledgements

We acknowledge the contributions of Alicia Keating and Jessica Brown, who supported this project as research assistants, and Emily Hall, who completed a summer scholarship for the project.

We gratefully acknowledge Warren and Mahoney for their substantial in-kind support during the initial stages of the project.

Our deepest gratitude goes to all interview participants – this report would not have been possible without your insights and generosity.

Abstract

This report examines the opportunities and challenges of adopting bio-materials in Aotearoa New Zealand construction, supported by a literature review and 35 interviews with relevant stakeholders. Bio-materials promise significant carbon reductions, health benefits, and innovation potential, yet face barriers including limited awareness, regulatory gaps and industry conservatism. Findings highlight drivers and enables such as hands-on experience, professional guidelines, and supportive policies. The report presents 17 targeted recommendations to build knowledge, foster social support, improve regulations and scale niche innovations. The report calls for a coordinated, multi-level approach to accelerate the transition to bioeconomy in construction.

Keywords: Bio-materials; construction industry; bioeconomy transition; decarbonisation; sustainable building materials

List of abbreviations

BRANZ – Building Research Association New Zealand
EPDs – Environmental Product Declarations
EU – European Union
GDP – Gross Domestic Product
IPCC- Intergovernmental Panel on Climate Change
LCA – Life-cycle assessment
MBIE – Ministry of Business, Innovation and Employment
MfE – New Zealand Ministry for the Environment
MoE – New Zealand Ministry of Education
MPI – New Zealand Ministry for Primary Industries
NZGBC – New Zealand Green Building Council
OECD – Organisation for Economic Cooperation and Development
R&D – Research and development
SIPs – Structural Insulated Panels
UK – United Kingdom
UN – United Nations
UNEP – United Nations Environment Programme
US – United States of America

List of figures

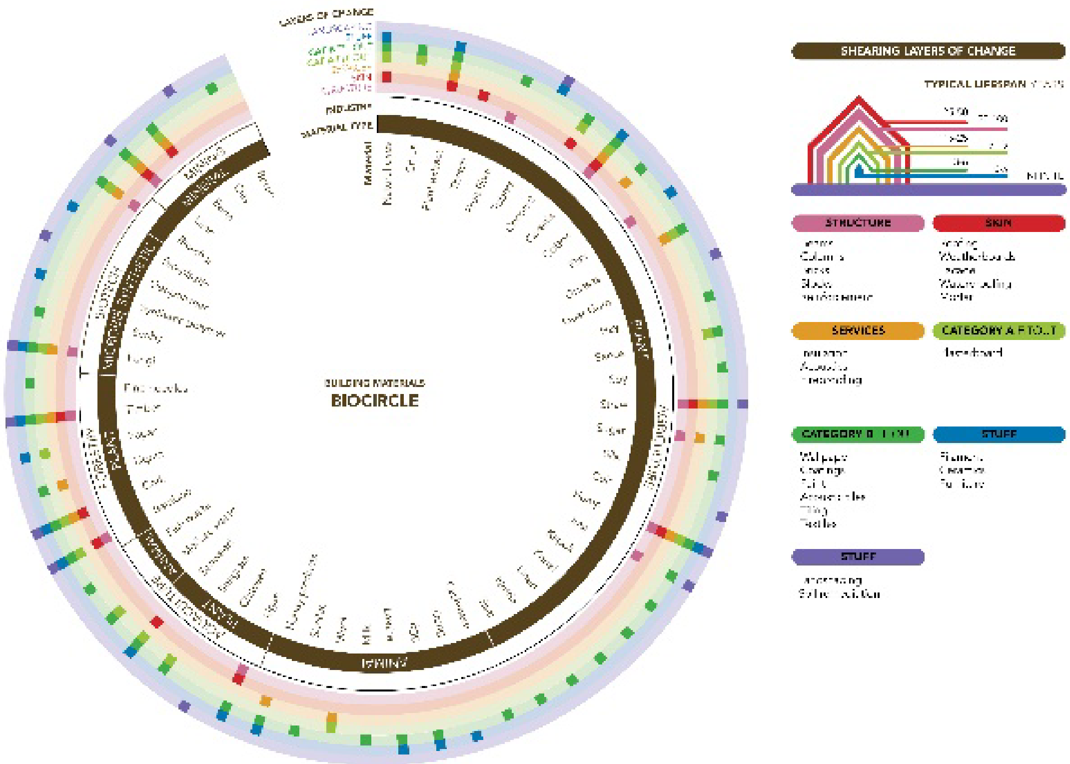
Executive summary

A literature review has demonstrated that transitioning to bio-materials in construction offers substantial opportunities.

This literature review has established that there is a wide range of benefits associated with transition to a bioeconomy in construction. **Bio-materials have the potential to drive radical decarbonisation, with estimated emission reductions of up to 40% by 2060 in many regions.** In addition to environmental benefits, natural, bio-based, bio-materials are also associated with a number of psychophysiological benefits. Direct personal experience of these materials is essential for both understanding their nature and experiencing their full psychophysiological benefits.

Globally, innovation in bio-materials is on the raise, including the development of novel and the reformulation of the traditional natural materials. In Aotearoa New Zealand, novel bio-materials have already received strong professional and public interest through experiential, hands-on, research exhibitions. However, while regulations supporting a transition to greater adoption of bio-materials are starting to emerge worldwide, significant regulatory challenges remain.

Today, bio-materials are available for all types of architectural applications – from structural components and building envelope to services, interior fitouts, furnishings and landscaping elements.



See Figure 6: Building materials biocircle.

Increased use of bio-materials in construction could raise demand for agricultural land and products, potentially creating supply bottlenecks. To prevent such issues, **the transition to bio-based building materials should align with agroecological principles – supporting biodiversity, avoiding competition with food production and climate mitigation, and ensuring true sustainability.** This intersection with agricultural activates appears to be currently contributing to inaccuracies in lifecycle assessment (LCA) calculations for bio-materials, highlighting one critical area for further refinement and improvement.

In addition, recognition of Māori as kaitiaki under Wai262 is foundational to ethical engagement with bio-materials and the establishment of reciprocal relationships. Bio-material investment should consider partnerships with Māori-owned opportunities that are grounded in Te Ao Māori, contemporary social and legal frameworks, and driven by iwi and hapū whanaungatanga.

This report presents findings from 35 semi-structured interviews conducted with a diverse range of stakeholders to better understand current perspectives on bio-materials in built environment. Participants were selected through a combination of representative and convenience sampling, with a focus on leaders in bio-material innovation and development, as well as architects, designers, builders, researchers, and policymakers. Participants were predominantly from Aotearoa New Zealand, but also included international leaders in the field.

Interviews identified a reasonably small number of very powerful key Drivers for the adoption of bio-materials in construction. These are:

Driver 1: Bio-materials, natural and bio-based materials, are preferred by people.
Driver 2: There is a growing interest in bio-materials.
Driver 3: Clients are asking for bio-materials.

Interviews identified a greater number of key Barriers than Drivers for the adoption of bio-materials in construction. These are:

Barrier 1: General population has limited knowledge about bio-based and bio-materials available for construction.
Barrier 2: Some of bio-materials are still experience stigmatisation and other challenging perceptions.
Barrier 3: Risk of the unknown: it is unclear who in the industry should take the risk of the early applications of bio-materials.
Barrier 4: There is a perceived or real higher cost of bio-materials.
Barriers 5: Externalised costs of many conventional materials lead to greenwashing, making bio-materials appear less favourable than they are.
Barrier 6: There are issues with scaling supply and production in Aotearoa New Zealand.
Barrier 7: Incumbent construction industry in Aotearoa New Zealand is conservative and entrenched, resisting change.

Interviews identified three sets of three interrelated Enablers, resulting in an impressive range of possible interventions to enable greater adoption of bio-materials in construction. These are:

Capability Enabler 1: Direct hands-on experience of bio-materials is important for aiding their uptake.

Capability Enabler 2: Case study projects showcasing bio-materials aid their uptake.
Capability Enabler 3: Semiformal education in specialised interest groups aids within-niche uptake of bio-materials.

Industry Enabler 1: "Drop-in solutions" can aid introduction of bio-materials into the business-as-usual.
Industry Enabler 2: Professional guidelines and recommended practice cases can help increase confidence of professionals when working with bio-materials.
Industry Enabler 3: Upskilling professionals for working with bio-materials can help broader uptake.

System Enabler 1: Planning for long-term intergenerational approaches is needed, and it highlights bio-materials as part of the solution.
System Enabler 2: Regulations, support from government and banks could aid faster transition to bioeconomy.
System Enabler 3: Linking bio-materials uptake with other industry trends could aid faster transition to bioeconomy.

The results of the interviews were visually summarised in Figures 8 and 9.

Figure 8 provides a visual overview of the identified drivers, barriers and enablers.

Figure 9 outlines suggested actions to support the adoption of bio-materials in construction, organised into three ambition levels: Seed, Grow and Thrive. It also illustrates how early actions can drive progress in later stages and helps changemakers select suitable strategies based on their goals and areas of focus.

Recommendations:

When examining the transition to a bioeconomy in construction through the lens of socio-technical transitions, four key areas for broad intervention emerge:

- Recommendation 1: Establish a clear, consensus-based definition of natural, bio-based, bio-materials for use in construction.
- Recommendation 2: Commit to a sustained effort to build broad public and industry support for a shift toward bio-based construction economy.
- Recommendation 3: Develop and implement a multi-level strategy to accelerate and strengthen the transition to bioeconomy in construction.
- Recommendation 4: Support emerging products in moving from niche innovations to mainstream adoption, while simultaneously developing the necessary infrastructure to enable wider uptake.

The transition to a bioeconomy in construction should be supported through the development of necessary new knowledge using following strategies:

- Recommendation 5: Develop professional guides and practical guidelines for using a wide range of bio-materials in construction.

- Recommendation 6: Establish hands-on training programmes with bio-materials for professionals in the construction industry.
- Recommendation 7: Promote bio-materials to the general public and the practitioners through activities such as tradeshows, showcases, hands-on workshops.

Building strong social support can also help accelerate the adoption of bio-materials in construction:

- Recommendation 8: Foster strong networks and connectivity through awareness-rising activities that promote use of bio-materials in construction. Support these efforts through research funding for bio-materials development or by stimulating their uptake in construction.

The transition to a bioeconomy in construction should be supported through the development of the following regulatory and government frameworks:

- Recommendation 9: Ensure that regulatory frameworks provide equal opportunities for the conventional and bio-based materials. Ensure LCA and EPD data for bio-materials is robust.
- Recommendation 10: De-risk uptake of bio-materials in construction by creating procurement pathways which support innovation; introducing manufacturer warranties to address unfamiliarity; and by assisting start-ups with material testing.
- Recommendation 11: Mandate bio-materials in government funded building projects.

The following recommendations outline key approaches for scaling niche bio-materials innovations for broader market adoption:

- Recommendation 12: Simultaneously develop drop-in solutions which work within existing rules (fit-and-conform) and radically innovative approaches how to work with bio-materials (stretch-and-conform).
- Recommendation 13: Use common niche market strategies, such as starting with imports (import-based seeding) and targeting simpler applications first (beachhead strategies), but complement them with actions that support boarder systemic transformation.
- Recommendation 14: Where feasible, incorporate agricultural waste into bio-materials for construction and actively promote its benefits.
- Recommendation 15: In the early stages of the transition, target early adopters, such as younger generations who tend to be more environmentally engaged and ready to innovate.
- Recommendation 16: Initially, target residential projects, retail fit-outs, and similar interior applications to showcase early use of bio-materials.

Complementing all of the above, enriching the meaning associated with bio-materials has been identified as a key approach to further support behaviour change toward broader adoption:

- Recommendation 17: Develop and enrich the perceived value of bio-materials by linking them with other positive concepts such as the bioeconomy, circular food systems, and related sustainability themes.

Table of Contents

1. Introduction

Bio-materials are increasingly seen as an important part of the solutions needed for a lower-carbon built environment. Using bio-materials within the built environment could contribute to resolving three major global issues: (1) combating climate change, (2) improving global material flows by increasing circularity and decreasing use of extractive, high-energy materials, and (3) improving a range of human health and wellbeing parameters.

Materials and material flows are starting to be recognised for their significant contribution to the triple planetary crisis: climate change, air pollution and biodiversity loss (UNEP, 2024). Globally, materials generate as much as 55-60% of greenhouse gas emissions through their extraction and processing (UNEP, 2024). Global material flows are responsible for 40% of the adverse effects associated with particulate matter exposure, and for over 90% of biodiversity loss and water stress resulting from land use (UNEP, 2024). Yet, if continuing current trends, by 2060, total material extraction is projected to increase by 60% (UNEP, 2024). Many of the conventional building materials are energy intensive, or have other issues with the extraction or toxicity, or limited circularity, which is why in 2023, United Nations Environment Programme (UNEP) has made a science-informed recommendation that an urgent shift to regenerative, low-carbon, bio-based building materials and material practices is needed (UNEP, 2023a). Truly regenerative materials can help incentivise biodiversity, help manage carbon cycle and offer potential for "radical decarbonisation" with estimated savings of up to 40% of emissions by 2060 in many regions (UNEP, 2023a). This is especially important as the 2023 IPCC Assessment Report warned of the need to reduce emissions by up to 50% by 2030 (IPCC, 2023). Ripple et al. (2024) report that emissions associated with fossil fuels are at an all-time high, and that we could be on track for 2.7 degrees of global warming from pre-industrial levels by 2100, well above the 1.5 degree target pathway set out in the 2015 Paris Agreement (Ripple et al., 2024; UNEP, 2023b). A shift to low-carbon materials is urgently needed for the built environment.

Recent decades have also witnessed an increase in research which has shown a strong positive influence of exposure to nature on psychophysiological wellbeing (Hartig et al., 2014; Frumkin et al., 2017), and a growing body of literature has emerged asserting that bio-materials can have similar beneficial influence on inhabitants (Burnard & Kutnar, 2015; Mfon, 2023; Crippa et al., 2012; Barrett & Barrett, 2010; Han, 2010; Vincent et al., 2010; Raanaas et al., 2011; Li et al., 2012; Gladwell et al., 2012; Karana & Nijkamp, 2014; Barrett et al., 2015; Overvliet et al., 2016). Bio-materials have been shown to be capable of bringing benefits of the connection to nature into the built environment, and studies have shown their beneficial effects on stress response, blood pressure, pulse, brain activity, etc. (Burnard & Kutnar, 2015; Shah, 2024; Tsunetsugu et al., 2007). More recent research suggests that indoor materials might be positively influencing the indoor microbiome, which is in turn directly related to human health (Gilbert & Hartmann, 2024). Therefore, an increase in use of bio-materials in the built environment could contribute to a number of much needed improvements.

1.1. Defining bio-materials

Currently there are no fully confirmed definitions what bio-materials are. Even in bio-medical technology, where bio-materials are used as implants, these are defined by their function (that they are replacing biological material within a body) and thus include materials of both organic and inorganic in origin (Hudecki et al., 2019). Similarly, in fashion, bio-materials are defined by some as an overarching term that includes bio-based materials which might be bio-synthetic, bio-fabricated or bio-assembled (Borst et al., 2020). Even the UNEP report from 2023 omits the definition of bio-materials when encouraging a shift to regenerative, ethically produced, low-carbon earth- and bio-based materials (UNEP, 2023a). Rather, they signal potential for positive inclusion of a greater use of timber and wood, bamboo, and other lingocellulosic materials from forestry, agriculture and other residues.

Based on a comprehensive review of bio-materials globally, it was established that for the purpose of this report, bio-materials are grown by biological organisms like plants, animals, bacteria, fungi and other life forms, either in full, or in combination with other materials as biocomposites. These are regenerative materials which can be grown over and over again. Because bio-materials are typically derived from biological sources, they are generally also low in carbon emissions. In some cases, they may even be carbon-negative, sequestering more carbon during their growth than what is released during their entire lifecycle. Bio-materials may also support an increase in biodiversity through the cultivation of native and locally grown bio-organisms. Some are made from agricultural waste and similar by-products, while many are likely to biodegrade or compost at the end of use, offering waste-free end of life and supporting circular economy. As regenerative materials, bio-materials are also capable of stimulating social, cultural and psychological benefits.

This definition of bio-materials also shows that there is a significant overlap between bio-materials and bio-based materials, and to an extent with natural materials. Therefore, throughout this report bio-materials and bio-based materials should be considered as interchangeable, and generally as natural materials.

1.2. Existing regulatory and other settings

In some parts of the world, the shift to the bio-materials is already led from the top-down either directly or indirectly. Directly tackling the uptake, in 2022, France introduced RE2020 law which required all state-funded buildings to be composed of at least 50% timber or other bio-based materials (MTEH, 2024; Graffi-Smith, 2021). Also, there are over 23 national roadmaps worldwide for bioeconomies, including 12 operational strategies such as the EU Bioeconomy Strategy (2018), Finnish Bioeconomy Strategy (2014) or the US Department of Agriculture's BioPreferred programme which support and enforce mandatory purchasing of products with a set minimum bio-based content (EU, 2024; USDA, 2024).

Bio-materials also have significant potential for achieving circularity, lower embodied carbon in buildings, and other sustainability benefits, and there is a range of shifts currently undertaken to achieve improvements in those areas. Worldwide, there are over 40 national circular economy strategies, notable are Australia's new National Circular Economy framework (Taylor, 2024), Europe's over 33 national roadmaps, and the EU Green Deal's Circular Economy Action Plan (Chatham House, 2020). The European Union's recently revised Energy Performance of Buildings Directive (EPBD) includes requirements for new builds to disclose embodied carbon from 2030 (European Commission, 2024). Jointly these shifts signal a clearly emerging direction of moving building materials towards renewable materials and practices which are most achievable through the use of bio-materials.

In Aotearoa New Zealand, the economy is in early stages of shifting to be more circular and bio-based, with Free Trade Agreements with the EU, UK, and the Closer Economic Relations Sustainable and Inclusive Trade Declaration with Australia which include circular economy provisions, and the Ministry of Business, Innovation and Employment (MBIE) commissioning research into the Circular Economy and Bioeconomy (MBIE, 2024), including construction sector investigations. The Aotearoa New Zealand Waste Minimization Act (2008) also provides research and development grants and incentivizes circular material use through waste disposal levies (MfE, 2024b).

Unfortunately, uptake of bio-materials might be challenging because of existing preconceptions against them. For example, some bio-materials are associated with controversial issues such as genetic engineering or might be experiencing lingering stigma (e.g. against industrial hemp due to association with cannabis) (Jo et al., 2023; Madusanka et al., 2024; EU, 2023; AHC, 2022). In Aotearoa New Zealand, the Hazardous Substances and New Organisms Act (HSNO) (1996) was prohibitive of genetic engineering, although 2024 marked government plans to end the thirty-year moratorium (Collins, 2024). Aotearoa New Zealand's new genetic engineering regulations are likely to modelled after Australia's Gene Technology Act's (2000) strict regulations on non-food GMOs, especially regarding environmental impact and biosafety. Currently in Aotearoa New Zealand, hemp is classified under the Misuse of Drugs Act (1975), Medicines Act (1981) and the Hemp Regulations (2006) which jointly allow production under strict licensing and compliance with limits for the psychoactive component of plants: tetrahydrocannabinol (THC) (NZHIA, 2024). The Biosecurity Act (2003) and the HSNO regulates bio-materials border-crossing and introduction of exotic species (MPI, 2020). The Conservation Act (1987) protects the collection and use of native flora, such as fungi. Therefore, overall, Aotearoa New Zealand has some of the strictest biosecurity regulations in the world, which could present limitations for development of bio-materials.

In Aotearoa New Zealand's built environment, pressure to meet net-zero 2050 goals creates regime tension and opportunities for sustainable niche-innovation uptake. The 2025 update of the Building Code will require inclusion of embodied emissions data (Jamieson, 2023) to support development of 2026 carbon caps. Government programmes, like the 2020 Carbon Neutral Government Programme and Building for Climate Change programme, mandate low-carbon ministry procurement and for government buildings with a capital value over NZ$9 million, from 2023, to achieve NZGBC's five GreenStar rating, which credits low-carbon, circular materials and innovation. Additionally, the Ministry of Education's Innovative Learning Environments programme (2018) mandates quality, non-toxic infrastructure for schools (MoE, 2018) which indirectly supports non-toxic, natural material uptake.

Over the last decade, mass timber construction has become more common in a number of countries, including the Australasian region (Evison et al., 2018). Certifications like LEED, BREEAM, and the Living Building Challenge add to pressure to increase uptake bio-materials in construction (MTEH, 2024). A number of professional organisations are holding conversations about bio-materials: in the last year or two, panel discussions, webinars, and similar about bio-materials have been facilitated by organisations such as the Living Building Institute, Passive House Accelerator, and locally by the New Zealand Green Building Council (NZGBC). At the same time, some of the more developed innovative bio-materials are starting to receive greater recognition, hemp through the Global Hemp Summit which has become a regular conference series (https://www.globalhempsummit.co/), and mycelium is included as topic into conferences about structures and architecture (https://www.icsa2025.com/). Awards about innovation in green space, such as the Green Product Award (https://www.gp-award.com/en) and large industry exhibitions such as Sustainable Industry Week (https://www.sustainableindustryweek.com/) are also increasingly dominated by applications of bio-materials (Figures 1-2). Jointly, these show a really vibrant interest in solutions bio-materials can offer.

Figure 1: Straw structural insulated panels (SIPs) exhibited at the Passive House, Wellington, New Zealand, 2024.

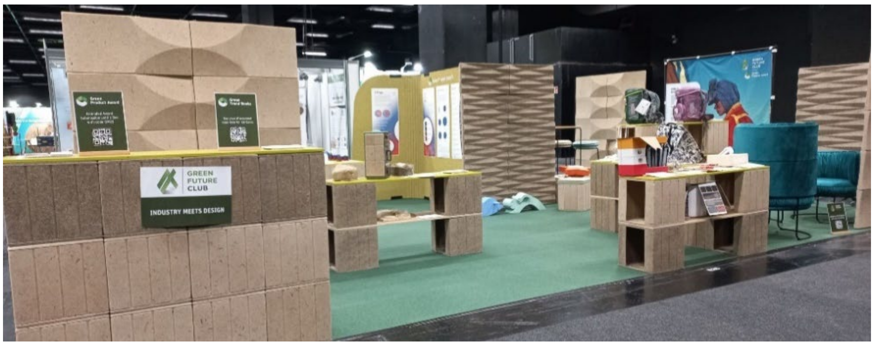


Figure 2: Green Product Award stand at the Sustainable Industry Week in Cologne, Germany, 2024. The most visible elements are partitions and blocks made out of compressed hemp or flax. A range of smaller products containing bio-materials are also visible.

Support for action is also strong among practitioners in Aotearoa New Zealand, with research showing that 92% of Aotearoa New Zealand built environment respondents believe action to reduce emissions is essential, and 87% support initiatives to reduce whole-of-life embodied carbon (MBIE, 2021a). Unfortunately, the same study also reported that 79% of local practitioners report barriers to taking action to reduce emissions (MBIE, 2021a). One existing barrier to improving sustainability of building materials in Aotearoa New Zealand is the high reliance on imports: 90% of construction materials sold are either fully imported or contain key imported components (EBOSS, 2021). Other analyses have shown that, apart from timber, no other bio-based materials take a noticeable share of currently used building materials in Aotearoa New Zealand (Clarke & Lockyer, 2022) and that even for engineered wood products more information and upskilling is needed (Carradine, 2020). Therefore, currently bio-materials are in the very early stages of uptake in Aotearoa New Zealand and it is reasonable to assume that many in the industry are not even fully aware of such options.

1.3. Project aim and outline of the report

This situation of the increased levels of interest in bio-materials, scientific recognitions that bio-materials might play a critical role in solving current triple planetary crisis, and limited current uptake of bio-materials other than timber, makes it important to investigate what is needed in Aotearoa New Zealand to enable a transition to greater uptake of bio-based building materials.

This project was set out to investigate what are the barriers and drivers for accelerating uptake of bio-materials in Aotearoa New Zealand's building industry. However, because uptake of bio-materials is currently still in very early stages, the focus of investigation is not on progressing uptake of bio-materials into mainstream, but rather on the increase of momentum and scaling of innovation to a higher rate of early adoption. The core assumption was that once there is an understanding of what helps or hinders the uptake, it will be possible to identify intervention points suitable to stimulate acceleration. Therefore, the project has two interrelated goals: to provide up-to-date information on bio-materials and their readiness for use in the building industry, and to examine how their adoption can be stimulated by intervening at the level of common perceptions and through behaviour change strategies. For both parts a “brand agnostic” approach was adopted, reflecting BRANZ practices, which means that some aspects of the discussion remain more general than specific.

The report opens with a review of the existing context on bio-materials (Section 2). This includes a high-level introduction to what is currently available, culminating in the introduction of the building materials biocircle which visually summarises the main findings of this review (Section 2.1). Two important aspects to be considered in relation to bio-materials follow: the potential adverse impacts on food production (Section 2.2), and a review through the mātauranga Māori lenses (Section 2.3). This is followed by an introduction to a set of theories of change (Section 2.4) and existing studies on perception of bio-materials (Section 2.5). Jointly, these reviews set the scene for the rest of the report.

Section 3 discusses methodology of the study, which used interviews as the main data collection technique. Section 4 reports on the results of the thematic analysis by grouping those into drivers, barriers and enablers, visually summarises those in Figure 8, and discusses the results. Complementing the thematic analysis, an analysis of the specific actions suggested by the participants was also undertaken. Those results are reported in Section 5, discussed and eventually visually summarised in Figure 9. Section 6 brings together the insights from all completed analyses, discusses those and provides recommendations.

2. Bio-materials Context

This section outlines the context and background upon which the rest of the work was developed.

2.1. Available bio-materials

A review of existing bio-material products showed that while a range of traditional bio-materials are still in use, a range of novel bio-materials are also currently emerging. Jointly, these tap into effective use of a very broad range of materials produced by bio-organisms.

2.1.1. Traditional bio-materials

Over the centuries, vernacular architecture developed a range of solutions for how to build with grown materials, and that included solutions to extend durability of the elements (for example, by impregnating wooden roof shingles with sap released from shingles themselves), but also how to embrace to perishability of material offering easy replacement (Radivojević et al., 2017). Some of the traditional materials, are still seen as sustainable, ecological bio-materials such as timber, earth and straw building.

Timber is one of the well-established building materials, both historically and currently, receiving much interest. Because of the extent of work focused on timber, the focus of this investigation is skewed to give more attention to other, generally less established bio-materials.

Generally using locally available materials, earth building is practiced in Aotearoa New Zealand and around the world. Several methods, such as loadbearing rammed earth, cob, and pressed mud bricks among the more common (Walker & Morris, 2021). These methods range in material density and provide ranging performance benefits in terms of both thermal and structural performance. Aotearoa New Zealand's earth building standards accommodate this spectrum of earth building materials and techniques (Standards New Zealand, 2024). The first editions of Aotearoa New Zealand's earth building standards, NZS 4297:2024, NZS 4298:2024 and NZS 4299:2024, were published in 1998 and were the first of their kind in the world (Walker & Morris, 2021; EBANZ, 2024). These standards were recently revised in late 2024 (Standards New Zealand, 2024) and to date, there has never been a reported failure of an earth building built accordingly with the standards (Walker & Morris, 2021). In terms of production, the standards also set out testing requirements for producing earthen materials from soils on-site (Standards New Zealand, 2024), and there are some prefabricated products entering the market, such as adobe veneers and pressed mud bricks.

Straw is a common agricultural waste product, the bales come in a standardized size and can be laid flat or on edge depending on the performance requirements of the project (Quinn, 2022). Strawbale has also been successfully used for centuries, but also more recently in certified passive house projects in Aotearoa New Zealand, highlighting its potential for high-performance housing (Sustainable Engineering, 2024). Strawbale construction in Aotearoa New Zealand can be load bearing and non-load bearing, although the latter is more common (BRANZ, 2010). In the most recent revision to the New Zealand earth building standards, NZS 4297:2024, NZS 4298:2024 and NZS 4299:2024, the scopes were widened to include strawbale, among other lower-density light earth methods (Standards New Zealand, 2024). As well as raised in-situ strawbale, there are a number of locally produced panelised systems coming onto the Aotearoa New Zealand market, mainly as structural insulated panels (SIPs), although currently such systems are not covered by the standards (Standards New Zealand, 2024). Compressed straw panels also exist on the market, and currently there is much innovation on how else agricultural waste, such as straw could be used in building materials.

Therefore, in Aotearoa New Zealand there are standards and guidelines needed to support the use of traditional bio-materials, like timber, straw and earth. Already more innovative applications of the same materials such as straw SIPs or compressed straw panels might experience greater regulatory barriers.

Other more traditional bio-materials include wool, bamboo, cork, and a number of various grasses and reeds. Complementing those, linoleum as an early example of successful biocomposite. Developed in 19th century, linoleum is made by combining oxidised linseed oil with resins from pine threes, wood flour, cork, and limestone fillers, with added pigments, which are then pressed onto a cloth to make linoleum sheets (Petrović, 2017). Some of these are also easy to use in current construction in Aotearoa New Zealand, like wool, cork and linoleum, while others might experience regulatory challenges, depending on the application, like bamboo, grasses and reeds.

2.1.2. Novel bio-materials

In contrast to traditional materials, a range of newer bio-materials have also emerged. Of those, hempcrete is the most established (Figure 3). Hempcrete was developed in France in the 1990s (Florentin et al., 2017) and has been growing in popularity and production volumes since. It can be used as a bio-aggregate non-structural material composed of hemp hurd, the woody inner fibres of the industrial hemp plant, and a mineral binder (typically lime or magnesium-based) (Magwood, 2016). This is similar to how existing wood-wool and cement boards are made. Hempcrete may be cast in-situ, or precast into block or panel systems. Hempcrete is an effective thermal insulation material, with additional unique hydrothermal and occupant health benefits such as passive moisture buffering (Tran Le et al., 2010). Hempcrete can be carbon-neutral or carbon-negative, assuming domestic production and supply chains (Bošković & Radivojević, 2023). There is active and ongoing work in Aotearoa New Zealand to increase the growth and processing facilities available for industrial hemp (Venture Taranaki, 2022), as well as ongoing development of locally produced binders. In Aotearoa New Zealand, hempcrete construction uses existing earth building standards NZS 4297:2024, NZS 4298:2024 and NZS 4299:2024 (Standards New Zealand, 2024).

Mycelium biocomposites is one of the bio-materials with increased recognition of possible usefulness for the built environment (Figure 4). Reportedly, mycelium biocomposites were first developed in 2007, by two undergraduate students at the time: Eben Bayer and Gavin McIntyre (Ecovative n.d.). Mycelium is the vegetative part of a fungus, consisting of a network of fine white filaments which can easily grow around a range of biological materials, such as wood shavings, hemp hurd, shredded cardboard, used up coffee grounds etc., binding those into mycelium biocomposites. The production process requires no energy, is reasonably fast, and mycelium can be grown in the dark (Holcim Foundation 2014, 61-64). After use, the material is generally compostable (Mayol 2012, 87). There is some natural shrinking and dimensional unpredictability of the material while it is grown, and depending on the finishing steps (Walker, 2022). In architectural applications, mycelium biocomposite has been used as bricks, as thermal or acoustic insulation, in a range of interior wall applications, but has also been successfully used for outdoor pavilion structures. In Aotearoa New Zealand, currently use of mycelium biocomposites is not regulated.

Figure 3: Hempcrete samples of different binder-to-aggregate ratios.

Figure 4: Mycelium biocomposite blocks.

The review of existing bio-materials products globally established that a number of more recent products use compression or other ways of combining natural fibres or agricultural waste into building materials. Figures 2 and 5 show some samples of the emerging bio-materials of this nature. There are already products on the market which use flax, jute, hemp, kenaf, reeds, pine needles, husks from rice, corn and coconut, straw from wheat, barely or even grass clippings. Although some of the products in this broad group might use natural or synthetic resins or glues to achieve the composite, an increasing number of these is assembled using lignin in the used bio-material and pressure. Consequently, the proportion of natural material can vary from 10% to 100%. Some imported products of this type are already available on Aotearoa New Zealand market, after addressing biosecurity concerns. Because biosecurity can present a barrier for easy import of grown products from other parts of the world, and because of adverse impacts of shipping, it is important to develop local markets with locally grown agriculture.

Figure 5: Samples of some of the emerging bio-materials.

In recent years a number of bio-based insulation materials have also been developed. In Aotearoa New Zealand, wool is already an established insulation product. Just as already discussed straw, hempcrete, and mycelium biocomposites have excellent insulation properties. New bio-based insulation materials include hemp-wool, wood-fibre batts, blown sheep's wool, and other new insulation materials are being developed.

Other exciting areas of novel development are materials which use fish scales, algae, seaweed or seashells. Others use kombucha scoby, bio-char or are working through improving existing practices with plastics by developing bioplastic replacements. Innovation includes efforts to develop natural pigments and dyes eliminating current reliance on synthetics for those.

2.1.3. Biocircle and bio-materials for this study

Based on the product review of the existing bio-materials, it was possible to develop Figure 6, which summarises the types of materials suitable as building materials into the Building materials biocircle. Biocircle shows in colour possible applications in buildings, using the framework of shearing layers of change (Brand, 1997) with structural applications in the inner side of the coloured ring, and less permanent applications towards the outer layers of the ring. Bio-materials are grouped based on their origin into materials sourced from agriculture, aquaculture, forestry, microbial, mineral and synthetic. Figure 6 visually demonstrates a high level of availability of materials for all types of architectural applications. It is especially exciting to see the increases in possible use of bio-materials for structure, skin and services layers of the buildings which have been conventionally seen as challenging for bio-materials because of their perceived or real lesser durability and weathertightness.

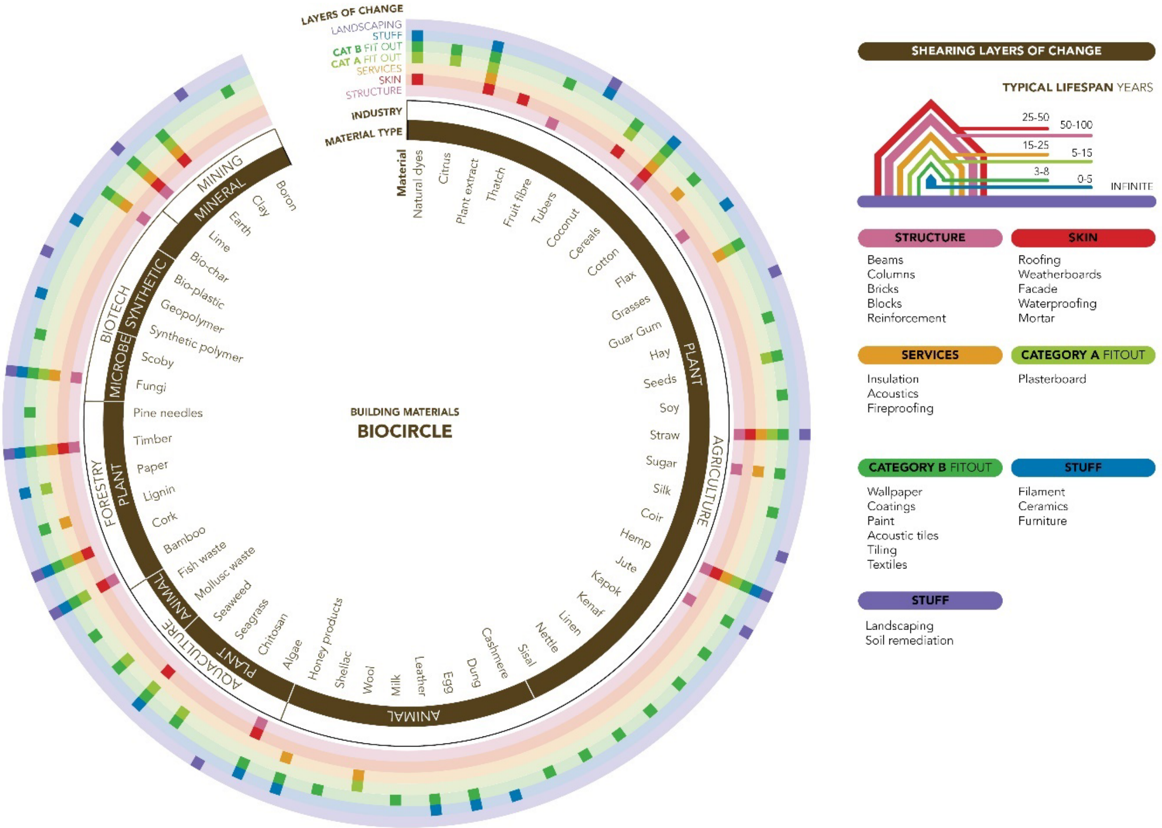


Figure 6: Building materials biocircle shows available bio-materials and their suitability for a range of architectural applications.

However, the building materials biocircle also makes it clear that many bio-material products are particularly suited for uses for the fitouts, in furnishings and landscaping layers of buildings. Such applications tend to be characterised by much more frequent adjustments during building's lifetime, often several to ten years (Brand, 1997). This is where bio-materials can be seen as ideal: durable for the needed realistic period of use, but also often compostable after the use, making the disposal a simple return into the nutrient cycle. A shift to a greater inclusion of bio-materials in such applications would allow decreased demand for materials which can last hundreds of years for temporary uses, which are currently associated with significant issues in disposal stage.

Inspired by the range of bio-materials evident in the Building materials biocircle, this report investigates the full range of materials as evident in the Figure 6. Therefore, the discussion that follows includes the more established and historical materials together with the emerging new innovative materials; materials which have received a varying level of scientific research about their properties; and many other differentiating characteristics, and discusses bio-materials as a heterogeneous group that brings these together. But as noted earlier, only limited attention is given to timber as the bio-material that is already the most established as a building material. Rather, a particular attention is given to the emerging and novel bio-materials, which are in very early stages of adoption, moving from innovation to early uptake.

2.2. Impacts from increasing use of bio-materials

Some unique challenges face large scale increase in use of bio-based building materials because their impacts are tricky to separate from other agricultural activities, both in terms of land use and calculations. A 2023 EU report signalled that an increase in consumption of bio-based materials could be competing with land use for providing goods for human use, either as food or materials, but also with the important role natural systems have for mitigating climate change and supporting biodiversity (Avitabile et al., 2023). Therefore, a transition to bio-based building materials should not compete with food production, climate mitigation and should support biodiversity. Therefore, bio-based building materials should be part of efforts to move to agroecology.

Unfortunately, examples of competition with food already exist. In late 2006, price of tortilla flour in Mexico more than quadrupled presenting real challenges for the large population of poor in Mexico and resulting in 'tortilla riots' (Runge and Senauer, 2007; García-Salazar et al., 2012). This price increase was the result of the rise in biofuel manufacture from corn in the US, leading to corn prices rising in the US, and an increase in purchasing corn from Mexico (Runge and Senauer, 2007; García-Salazar et al., 2012). Although often there are other societal complexities influencing events of this nature, and that was the case here, shifts to more sustainable practices should proactively work to avoid potential to contribute to similar issues. This is especially relevant given the strong association between agricultural land use and biodiversity loss and water stress (UNEP, 2024). This proactive prevention means that it is important to carefully evaluate potential impact of increase of uptake of bio-materials on food availability, especially if the bio-materials are using food sources for their manufacture, like corn, or the land otherwise used for growing food.

In 2023, Murray and Petrović completed an analysis of this nature on the example of hempcrete in Aotearoa New Zealand (Murray and Petrović, 2023). Basing the work on the information from the plans submitted at the resource consent phase of the Kāinga Ora Arlington housing development in Mount Cook, Wellington, that analysis showed that it would take 0.9 and 3.41 hectares of land to grow industrial hemp needed for five types of medium density units, or between 0.075 and 0.12 hectares per inhabitant. Comparing those figures to average agricultural land needs for yearly food which range from 0.13/0.14 hectares for vegan/vegetarian diets to 0.93 hectares for omnivorous (Peters et al., 2016), the results show that per occupant hemp agricultural land requirements were lower to build housing than for one year of food for all types of diet. On the other hand, industrial hemp is a fast-growing plant with bio-remediation properties for the soil, and it is typically harvested after 3-4 months which means that normally about three harvests would be possible from the same land (Murray and Petrović, 2023). This comparison also shows that even a small proportion of people moving from omnivorous diets to lower meat or no meat diets could lead to very significant reduction of global requirements for agricultural land for growing food, creating capacity to grow more building materials.

Other sources arrive to similar indication that transitioning to more plant-based meals or diets could have great benefits in supporting other aspects of transition to bio-economy. In 2023, out of 924 million tonnes of dry matter produced in EU from the agricultural sector, nearly half, 43% was used for animal feed and bedding, while 10% supported plant-based food for humans and 0.3% seafood (Avitabile et al., 2023). Although EU supplements its own production with imports of bio-based products, this 4:1 ratio in the biomatter needed to support land animal vs other food production is striking. However, there are other areas of possible significant increases of efficiency, given that almost one quarter of EU biomatter was consumed for energy as fuel (Avitabile et al., 2023).

An additional issue is how to calculate environmental impacts of materials which are waste from food production, such as straw from wheat and wool from sheep grown for lamb. Currently, in some LCA calculators, these appear less favourably than their conventional counterparts, especially when compared with materials which use recycled content of energy intensive materials (Blewden, 2024; Subasinghe, 2024). For example, in some data sets recycled polyester insulation and fibreglass (which often contains recycled glass) appear to have lower LCA than wool insulation (Blewden, 2024), while strawbale construction can appear to have very comparable or even higher LCA impacts than conventional construction (Subasinghe, 2024). Such data can discourage transition to bio-based building materials despite many other indicators of how valuable this would be. Therefore, a sustained effort is needed to resolve issues of this nature as the LCA data continues improving.

To summarise, as part of embarking to using food or agricultural land for growing bio-based building materials, evaluations should be undertaken that such transitions do not compete with food production, climate mitigation and support of biodiversity. One great advantage of the shift to bio-based materials is that many agricultural waste materials can be effectively used in building materials (see Section 2.1), which can avoid complexities of competing land use but also provides circular solutions for this waste. It is also important to note that waste from some agricultural processes might be already integrated into other production – for example much of straw is already used for animal feeding and bedding – but many opportunities to improve use of agricultural waste still remain. Another encouraging group of bio-materials are those grown in laboratory conditions, like mycelium biocomposites, which are unlikely to require similar evaluations (see Section 2.1). Nevertheless, any possible issues should be carefully evaluated, and a much greater care appears to be needed with how bio-based building materials appear in the emerging LCA calculators.

2.3. Embedding te ao Māori and mauri-enhancing bio-material lifecycles

In Aotearoa New Zealand an exploration of how mātauranga Māori and te ao Māori influence bio-material uptake is essential for understanding the alignment of cultural knowledge systems concerning traditional, indigenous, material use and the historical adoption of non-traditional materials. Within the context of Te Tiriti o Waitangi this analysis has significant implications for resource management, equitable sharing, and outcomes within the built environment (Waitangi Tribunal, 2011). Approaching these aspects from a partnership standpoint advances the ideal of the Wai262 report (2011) for a “twenty-first century relationship of mutual advantage in which, through joint and agreed action, both sides end up better off than they were before they started” (Waitangi Tribunal, 2011). This exploration highlights current and potential opportunities for te ao Māori to lead philosophical understanding and the practical uptake and application of bio-materials grounded in tikanga taiao and its associated frameworks.

2.3.1. Whanaungatanga and kaitiakitanga

Te ao Māori is grounded in concepts of whanaungatanga, or interrelatedness between people and nature, with accompanying obligations to nature, termed kaitiakitanga (Waitangi Tribunal, 2011; Roberts et al., 1995). Kaitiaki have relationships with land and non-human whanaunga that are locally specific, derived from a shared whakapapa with nature and inherited tribal histories connecting Māori to place across time (Roberts et al., 1995). As such, kaitiakitanga is understood through an intergenerational lens (Winter, 2020). These relationships between kaitiaki and place are defined through an acknowledgement of mauri, which is broadly understood as vitality, or essential energy/life-force in all living and non animate things (Barlow, 1991; Keelan, 2014). As well as having a spiritual dimension *mauri* (vital lifeforce) is can be legible in the environment as the holistic combination of observable factors: purity of freshwater; abundance, biodiversity, and behaviour of fauna and flora; energy consumption; and resource availability among many others (Warbrick et al., 2023).

This is seen in Yates (2021) contextualisation of planetary boundaries in the context of mauri ora, emphasising that humanity is not an external party to issues of ecology and biology, but rather contained within the bounds of the earth with all living things. Warbrick et al. (2023) offer the following whakataukī as evidence of the omnipresence of the earth: *Whatu ngarongaro te tangata, Toitū te whenua* / As people disappear, the land endures (p.1). Bio-materials which are grown by the natural world and used by humans sit within this reciprocal relationship between the natural and human worlds, and have the potential to contribute to the enhancement of mauri through practices which have powerful positive intentions in their core (Yates, 2021).

The pūrākau or story of Rātā is a seminal legend in Māori mythology with roots in Polynesia (Waitangi Tribunal, 2011). Rātā, who cut down a great tree in the forest, is admonished by the Tāne's kaitiaki who reassemble it with the following karakia:

Rātā ware, Rātā ware,
Noho noa koe ka tuatua noa i a Tāne,
Koia i whekii, koia i whekaa,
Rere mai te maramara,
Koia i piri, koia i mau,
Rere mai te kongakonga.
Koia i piri, koia i mau,
E tu Tāne, kia torotika to tu,
Tihe mauri ora!

Ignorant Rātā, ignorant Rātā,
You took liberty and felled Tāne,
Hear the thud, hear the sound (of the adze),
The chips fly hither,
Stick together, hold together,

The fine chips fly hither,
Stick together, hold together,
Arise Tāne, and stand straight,
Behold, he lives anew! (Waitangi Tribunal, 2011)

Rātā's narrative teaches that respect for the forest transcends mere resource extraction, recognising it as *atua* (a spiritual entity) (Waitangi Tribunal, 2011). Beyond seeking permission, Rātā must cultivate empathy and grasp the ripple effects of his narrowly focused actions on the interconnected natural world. Forests are portrayed not as inert landscapes but as living systems bound by *whanaungatanga* (kinship ties)—where every being, from the smallest unseen organism to the towering tree (children of Tāne-mahuta), sustains the *mauri* of the whole. The felling of a tree is never an isolated act: its loss destabilizes the entire web of relationships, just as the vitality of the system ensures the tree's survival. This reciprocity reflects a worldview where humans are *muka* or threads within the *kakahu* or cloak of life and the material world- not overlords.

Many *whakataukī* (Māori proverbs) affirm the vital interdependence between animals, materials, and the natural world. As the widely cited example states: *Unuhia te korito o te korari kei hea te korimako e ko, whakatairangi-tia, rere ki uta, rere ki tai… Ui mai ki au, he aha te mea nui o te ao? Māku e kī atu – he tangata, he tangata, he tangata."* / "Remove the inner shoot of the flax, and where will the bellbird sing? Let it ascend, fly inland, fly seaward… Ask me, what is the greatest thing in the world? I will say – it is people, people, people. This *whakataukī* illustrates how removing the korito (inner shoot, or *tamaiti*) of the harakeke (flax plant) not only kills the plant but destabilises its entire web of relationships. The loss reverberates through ecosystems, weakening interdependencies—from the korimako (bellbird) deprived of nectar to the broader ecological and cultural networks sustained by harakeke. Such teachings reject fragmented Western resource paradigms, instead positioning humanity (*he tangata*) as stewards embedded within, not separate from, these lifegiving systems.

2.3.2. Parahanga/ Waste products

Rātā's story is significant in conveying a tikanga (principle) of care for all aspects of the material world—including what we might deem unimportant or insignificant—as a way to maintain balance. When Rātā felled the tree, it created an excess or introduced the concept of "waste," something that demands deliberate attention and cannot be disregarded. The story implies that the offcuts and excess are respected and valued within the wider process of procuring the tree and its use. The world as an indivisible continuum of effects that are held in balance through our actions (Marsden & Royal, 2003) The use of materials is not confined to a process of extraction only, all aspects are managed, including responsibility for waste or excess.

Māori ontologies resonate deeply with contemporary concepts of upcycling and waste management. Materials like woodchips, often dismissed as waste in Western frameworks, are imbued with tapu (sacredness) across many *whakataukī* (proverbs) and ancestral narratives. For instance, Ngāti Wai tohunga (iwi expert) Te Wārahi Kōkōwai Hetarāka interprets the whakataukī: *…ko te kuha rere mai te maramara tupu whai ake…* / The wood chips that scatter during carving will follow to fulfil another purpose (Hetarāka, 2018). Here, maramara (woodchips) are reframed not as waste but as entities with agency, destined for renewal within interconnected systems. This mirrors the tapu/noa (sacred/ordinary) framework, where even by-products demand intentional care to avoid ecological or spiritual imbalance—a stark contrast to linear, extractive models of resource use.

Therefore, bio-materials design and thinking align with how cast-offs or waste products are respected in ways that unlock their potential for reuse or cyclic integration into a circular economy. The “danger” of maramara and kongakonga rākau (woodchips) emphasised in Rātā’s kōrero underscores the need to carefully consider their impact—to avoid negative disruption of other territories (material or ecological) and relationships within interconnected systems. In a contemporary context, this disruption parallels the environmental harm caused by slash waste (and silting) in the pine forest industry, where unmanaged by-products of production (e.g., unprocessed slash) create lasting damage to local ecosystems (waterways/beaches) during weather events (Smale, 2024). This exemplifies a Western approach to resource management, which often isolates discrete parts of a process rather than addressing systemic, long-term consequences for the broader environment and sustainable resource cycles.

The separation of by-products (or "waste") from their original use opens pathways for transformation. While woodchips might be returned to an existing system—such as compost or *wairākau* (fertiliser)—their integration into bio-material composites embodies a new potential, as suggested by the excerpt: *he tupu whai ake* / a new growth follows. This duality reflects a Māori ontological perspective: even discarded materials are never inert but instead repositioned as agents of renewal within cyclical systems.

Here an alignment is clear with products such as hempcrete which makes a useful building material by using hemp hurd, which commonly is a waste material from industrial hemp cultivated to use other parts of the hemp plant (Murray, 2024). Mycelium products are likewise able to utilise traditional biological waste in growing, such as wood shavings, hemp hurd, used up coffee grounds and much more (Walker, 2022). Reframing binaries such as waste/useful material, nature/culture, human/non-human, and space/time (Yates, 2021) through te ao Māori offers important philosophical insight into how bio-material uptake can be inflected by Aotearoa New Zealand’s cultural context.

Bio-materials hold transformative potential in rebalancing human-nature relationships by embodying *tikanga kaitiaki* (guardianship practices) to enhance the mauri of ecosystems. They provide tangible pathways to reimagine waste management and reuse through frameworks rooted in reciprocity. Unlike linear "take-make-dispose" models, bio-materials can reintegrate by-products into circular systems, reflecting *matauranga* Māori principles where nothing exists in isolation and all materials retain purpose across cycles. This shift not only reduces ecological harm but revitalises connections between people and *Papatūānuku*, positioning sustainability in alignment to cultural and ecological restoration.

2.3.3. Whānau, hapū, and iwi value chains for economic and ecological benefit

These principles stand in stark contrast to the land and resource management of external, often international parties, that take raw materials without genuine investment in communities. Disconnected approaches can be validated by international credentials lacking the holistic and local awareness of ecology and culture, as discussed by Smale (2024) in regard to Tairāwhiti’s pine forestry industry. In

Aotearoa New Zealand, pine, as an exotic tree, is less connected to place and invades natural systems, disrupting whanaunga relationships; this is a process that is driven by economic investment that is inattentive to place (Bellingham et al., 2023). However, external overseas investment although not always indifferent to the aims of Māori. Orongo Station in Te Tairawhiti is an internationally recognised example of when an investor sees the value of aligning to tikanga kaitiaki in a regenerative way with hugely positive ecological investment. (Barrett, 2013). This shows how partnerships as discussed by Wai262 (Waitangi Tribunal, 2011) can be of mutual benefit.

Māori ontologies present significant advantages for Māori whānau, hapū, and iwi and the taiao in the ownership of the wider chain of material supply, from planting to cultivation to use and the attentiveness to mauri that comes with local involvement over the entire resource growth and production. This is exemplified by the Ngāti Hine Forestry Trust's work to transition forestry land to native species through "patchwork" plantations, which is intergenerational in scope and grounded in the partnership of local mātauranga-a-hapū (hapu knowledge) with mātauranga Pākehā from Scion (*Ngāti Hine Leads Development of World First Indigenous Forestry Strategy*, 2022). Indigenous design of new planting strategy has been driven primarily by the motivation to mitigate against the wider environmental effects within their land holdings over the last 50 – 70 years. A collaboration that creates patchwork kuira forests dual native and pine (*Ngāti Hine Leads Development of World First Indigenous Forestry Strategy*, 2022).

The Tōtara Industry Pilot, with Te Taitokerau Māori Forestry, further highlights the importance of local value chains in their final report which speaks to retaining wealth in the community (Dunningham et al., 2020). This includes monetary wealth and local employment opportunities, but also local control over forest management and educational opportunities for local kura to teach about the natural world through bio-material production. Beyond a profit agenda, the Tōtara Industry Pilot has a major focus on social license to operate, based on long-term relationships and trust between stakeholders and producers (Dunningham et al., 2020). It is place-specific and mauri-attentive values that provide great opportunity for the production of bio-materials for a needed transition in the construction industry (Yates, 2021). These values are locally engaged with te ao Māori at the small to medium commercial scales (Dunningham et al., 2020). Dell et al. (2022) discuss various examples of these attitudes being particularly pertinent in Māori business. While these examples are in timber forestry, which as discussed has existing frameworks to lean on, there are opportunities for greater uptake of bio-material production within whānau/hapū/iwi collectives. These opportunities, for example in the hemp industry, must learn from established best practice for partnership and management.

2.3.4. Partnership and Te Tiriti

There are governance issues to be addressed regarding Te Tiriti o Waitangi and the commercial exploitation of some bio-materials, particularly regarding native species that may be taonga to particular kaitiaki groups or mātauranga a hapū. These are discussed in depth in the Wai262 report (2011). The concerns of commercial exploitation include genetic modification as a disruptor of whakapapa relationships of taonga species to kaitiaki. Nguyen et al. (2021) extend this discussion into the agglomeration of kōwhai species through hybridisation. Furthermore, intellectual property rights over traditional mātauranga or plant varieties that are granted to outside parties have been seen as a threat to indigenous knowledge (Waitangi Tribunal, 2011). The Wai262 report underpins the right of kaitiaki to acknowledgement, benefit sharing, and reasonable control over the use of culturally significant mātauranga and taonga species (Waitangi Tribunal, 2011). This extends beyond solely commercial ventures to the realm of knowledge creation, which Morgan et al. (2019) discuss in relation to public good-focussed research on mānuka that led to commercial opportunity without Māori consideration.

Although there are obligations that come with acknowledgement of mātauranga Māori or use of taonga species, the Waitangi Tribunal's Wai262 report (2011) asserts that these are not obstacles to entrepreneurial success; in fact, taonga status is an opportunity recognised by Nguyen et al. (2021) in their assessment of kōwhai as a timber resource. Other community businesses are able to engage with Wai262 recommendations by engaging with Māori collectives and can use this engagement as a positive element to promote their business; this is the case with Maharakeke Mushrooms, who supply the native *Pleurotus parsonsiae* species that was examined in Walker's (2022) thesis.

Te Ao Māori is, through understandings of whanaungatanga guiding whānau, hapū, and iwi value chains, understood to comprise an opportunity with bio-material uptake as a vehicle for partnership. This opportunity exists in mauri-focussed attention to nature, circularity and waste contextualised by tapu, and culturally uplifting engagement with community.

2.4. Theories of change

A higher rate of inclusion of bio-materials in Aotearoa New Zealand would require a change to a range of existing practices. Therefore, it is important to understand scholarship on change. With the increase of global agreements on the importance of climate action, a number of theories has emerged explaining climate behaviour and behaviour change in order to accelerate action. Those provide a useful context for the type of possible interventions to support raise of bio-materials in construction. This review included behaviour change approaches from psychology, social practice theory, but sustainability transitions, sustainability transition framework and tipping point challenges provided the most useful approaches for the nature of the considered change. Summary of the review follows.

2.4.1. Theories from behavioural sciences

When examining the motivation for taking a particular action, in psychology self-determination theory differentiates between the intrinsic (e.g. doing something because it is inherently interesting or enjoyable) and extrinsic motivation (e.g. doing something because it leads to a particular outcome) (Ryan & Deci, 2000). It is recognised that there are many external factors that can influence extrinsic motivating, including rewards (positive reinforcement), deadlines, directives and competition pressures which all shift people away from their intrinsic motivation (Ryan & Deci, 2000). This means that although it would be desirable for a shift to bio-economy if many people intrinsically desired to contribute to this effort, there would still be a great number of external factors pulling them theoretically either closer or further from this goal. Therefore, understanding of the external factors is needed.

According to Ajzen's theory of planned action and perceived behavioural control, perceived barriers for a certain behaviour, together with the directly observed barriers, can challenge the progression from an intention to the actual behaviour (Ajzen, 2012). Applied to the context of uptake of bio-materials this means that even if navigating construction of their own home and strongly committed to using bio-materials, people would experience perceived (e.g. lack of familiarity with similar examples) and actual barriers (e.g. builder declining to use bio-materials or challenges with procuring these). Those would work against the intention to use the bio-material becoming the actual behaviour. As a result, the client would either have to push against those these barriers, making their change of behaviour harder, or adjust their own intentions under these external pressures. This means that a better understanding is needed of the potential perceived barriers for greater uptake of bio-materials in construction.

These theories show that it is important to better understand the external factors which might be influencing the motivation or present perceived or actual barriers for action of an individual. Some of those factors are societal.

Developing upon the Pierre Bourdieu's *Outline of a Theory of Practice* (1977), a range of social practice theories have since been developed with an aim to explain the phenomena at a societal scale. In recent years, Shove's social practice theory examined reasons why practices are sustained, transformed or abolished (Shove, 2012), which can be useful when interpreting behaviour change in society. In this theory, objects, infrastructure, tools, etc. (all the physical items needed to complete a practice) are the "materials;" the emotions and motivations for the practice are the "meaning;" while the activities needed to understand and do the practice are the "competence." When those elements are linked together, they became a practice, and "practices emerge, persist and disappear as links between their defining elements are made and broken" (Shove, 2012). The theory assumes that for a change of practice, one of the core elements needs to change, which leads to adjustments to all other elements.

If considering increased use of bio-materials in construction through the social practice theory lenses, bio-materials are the "materials" although another important aspect of the "materials" are the rules, regulations and suitable design examples, which are all part of the infrastructure needed for greater use of bio-materials; the motivations for use are the "meaning," and that includes both positive and potentially negative associations with bio-materials; while the skills, knowledge and practices that the designers, builders but also clients, building inspectors, etc. need to effectively work with bio-materials are all part of the "competences." This means that currently some change might be needed for all three core elements of the Social Practice Theory, but also that there is a need for a careful understanding of the existing and potentially missing aspects for each of the elements. This study makes a contribution in more definitively describing each of the elements.

This review of theories from psychology and sociology which could potentially help with the greater uptake of bio-materials in construction have shown the need for a better understanding of the existing social dynamics, which this project aims to address.

2.4.2. Sustainability transitions theories

Sustainability transitions and related theories offer some very useful frameworks for this analysis, because they enable focus on the role of niche innovators and other dynamics common in early stages of transition. Sustainability transitions is a set of theories which develop upon the idea of socio-technological regimes, and that a shift in a regime can be stimulated (Markard et al., 2012; Kemp, 1994). Sustainability transitions are long-term, systemic shifts that are "goal-oriented, in the sense of addressing environmental problems," and "multi-dimensional, involving not only technological innovation but also changes in business models, user practices, public policies, infrastructures, and cultural meanings" (Geels, 2018, p. 6). They vary from typical historical transitions, which were generally driven by the innovation, because sustainable solutions are for the "collective good" and require innovation and implementation of that innovation. Another unique problem with sustainability transitions is that emerging technology does not always outperform incumbent technological regimes, neither in terms of price or performance, which can mean they might require socio-economic incentives to fully replace incumbents (e.g. taxes, regulatory frameworks) (Geels, 2011). Additionally, the construction sector can be seen as characterized by large incumbent actors with established assets (e.g. manufacturing infrastructure, distribution, trials) and consequently with strong influence on sustainable transition.

The multi-level approach to sustainability transitions assesses socio-technical systems across three levels: niche (where innovations emerge and develop); regimes (dominant and established systems of practice); and landscapes (exogenous forces and trends which pressure regimes e.g. climate change, economic crises, and cultural trends) (Geels et al., 2016; Kemp et al., 1998). Multi-level perspective theorizes that market adoption of niche-innovations occurs when multi-level levers align, such as: exogenous shifts exert pressure on regime to change; regime tensions generate window of opportunities for niche expansion; and "internal momentum" of niche-innovations leads to market-ready stage of development (Chan et al., 2020; Geels, 2002; Geels et al., 2016). Geels (2004) defines the socio-technical regime (e.g. construction industry in Aotearoa New Zealand) as "well-entrenched systems [...] which are stabilized by alignments between existing technologies, regulations, user patterns, infrastructures, and cultural discourses" and shape the actions and perceptions of incumbent actors. Regime innovation is often incremental due to various lock-in mechanisms: economic (e.g. sunk investments, economy of scale, decades of learning); social (e.g. status quo routine and mindset, social capital, user lifestyles); and political (e.g. opposition of incumbents favoured by policy, existing policy that favours incumbents).

As opposed to a single strategy, research argues regime-adoption requires a combination of levers engaging actors horizontally (e.g. niche engagement between researchers and entrepreneurs) and vertically (e.g. niche-regime engagements between engineers and researchers) is required (Auerswald & Branscomb, 2003; Chan et al., 2020). Transition management frameworks provide long-term visions, with both short and long-term objectives, require a broad range of actors, and can inspire mobilization of other social actors (Kemp & Rotmans, 2005). Collective and organizational action required include incentivisation, awareness raising, infrastructure and regulations (Chan et al., 2020). Further to that, the role of government in an innovation's pre-development phase is to promote participative discussions and to mobilize actor programs for system innovation to support take-off, whereas its role in acceleration phases is to push structural change through policy changes (Kemp & Rotmans, 2005).

Based on niche-development and diffusion research, Geels (2007) proposes that viable market-ready niche-innovations have (a) dominant design stabilized by iterative development; (b) support networks including powerful actors; (c) economy of scale and performance have improved and expected to continue; and (d) use in market niches, which amounts to more than 5% of market share. Additionally, expectations of performance need to become precise and accepted within the mainstream regime (Geels, 2011).

Criticisms of the multi-level perspective is that it generalises through its three levels, fails to provide rigorous models of action, and it is a "heuristic device" (Genus & Coles, 2008). This research appreciates the heuristic perspectives multi-level perspective provides, as it can guide stakeholders to "better think through the problem" (Porter, 1991), but also uses multi-level perspective in combination with a set of other theories.

Applied to Aotearoa New Zealand's context, sustainability transitions theories suggest that landscape pressures and regime tensions discussed in the introduction might be close to being aligned well enough to support uptake of bio-materials in construction. At a landscape level, regions worldwide have directly and indirectly influenced the uptake of bio-materials and circular materials in construction through regulation, mandates and incentives. Although regime actor mindsets are increasingly aligning with low-carbon construction, this alignment does not guarantee meaningful change. While attitudes toward environmental protection are related to intentions to purchase sustainable products, the perceived risk of these products often significantly hinders adoption (Sun et al., 2018). Ultimately, the extent to which niche innovations can mature and capitalize on windows of opportunity created by external pressures or internal regime tensions will determine whether industry ambitions translate into genuine environmental impact.

2.4.3. Sustainability Transitions Framework (STF)

Expanding upon sustainability transitions, Sustainability Transition Framework (STF) brings together four theories of change and proposes that there are core alignments between sustainability transitions theories, diffusion of innovation theory, change curve and the style cycle (Petrović, 2023). Figure 7 shows the alignment of the four theories into the STF, and each theory can be summarised as follows:

- Transition curve shows the four stages identified by the sustainability transitions theories: the predevelopment, take-off, acceleration and stabilisation into the new regime, and signals that predevelopment and stabilisation are periods when the obvious rate of change is slower, while the rate of visible regime change is faster during take-off and acceleration. However, sustainability transitions research gives great emphasis on the high level of complexities during the predevelopment stage (see section 2.5.2.).
- Diffusion curve is based on Rogers' classic work on diffusion of innovation which has since been expanded to include the chasm and the tipping point. It shows that in early stages the innovation is with the niche innovators and the early minority of adopters, who might even be the innovators, and it is only after the risky period of the chasm, that the greater uptake of innovation starts to take place, and many innovations do not arrive to that stage.
- The change curve is based on Kübler-Ross's grief stages, but since developed to show the emotional processing of organisational change. It indicates that in the early stages, while the innovation is being developed, many are in denial about the impending change, which is why they shift into anger and depression once it is clear that the change will be needed.
- The style cycle curve is based on Wincklemann's theories about cyclical, wave nature of changes of styles in art and architecture. It shows that the style moves from an archaic style to classical to decadent (Petrović, 2023).

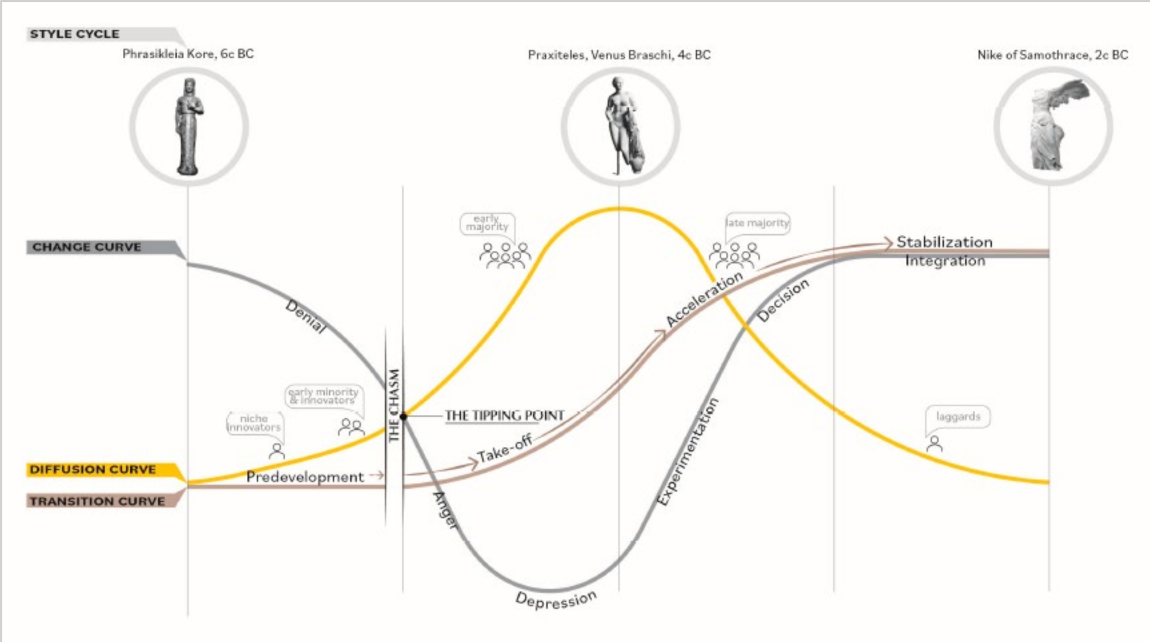


Figure 7: Sustainability Transition Framework (STF).

For this investigation of particular relevance are dynamics during predevelopment stage, and to an extent as the transition progresses toward take-off. This is because the level of innovation and uptake currently observed with bio-materials (see Section 2.1) is reflective of the niche innovation and very early adoption. During the predevelopment stage in addition to the critical niche innovation and increasing landscape pressures, discussed in Section 2.5.2, most of the population is in general denial of a change which might be coming their way, and the architectural or stylistic expression is still being articulated. This also suggests that care should be taken of the likely negative reaction of the many, once the transition gains momentum, and that proactively solutions how to manage that stage should be part of the predevelopment stage. It also suggests that clear articulation of the style of the new can aid the transition.

2.4.4. Risks when scaling uptake of innovation

One important aspect of innovation dissemination is that some innovations experience a take-off, while others struggle to gain traction. Many innovations remain confined to a niche for extended periods, gradually increasing in popularity and adoption. In order to understand this, several theoretical frameworks have examined the characteristics of the moment when the take-off occurs, offering valuable insights into the risks involved in scaling innovation. This moment has been discussed as the chasm, tipping point, the "valley of death," "Darwinian Sea," etc. Research shows the "valley of death," which takes place between invention and viable market diffusion of the innovation, can be as long as twenty to thirty years (Auerswald & Branscomb, 2003; Glanz, 2005). The term "valley of death" refers to the perspective that there is a capital gap during transition for niche innovations. Auerswald & Branscomb (2003) provide an alternative framing, the "Darwinian Sea" which acknowledges the contention for resources occurring between "big fish" and "little fish". Challenges for entrepreneurs in the "Darwinian Sea" include motivations for reduction-to-practice research; mismatch between technologist and business manager; break in funding for technical bridge between invention and innovation; and enabling infrastructure for scaling, suppliers, distribution, and upskilling. “Innovation gaps” can occur due to breaks or scarcity of funding for higher risk ventures, which typically need to provide business cases with reliable costing and performance before securing funding from venture capitalists, angel investors, and banks (Auerswald & Branscomb, 2003).

However, in Aotearoa New Zealand climate technology innovators, when compared to other small advanced economies, acquire below average funding, in regards to number of companies funded and investment amount, raising 19 times less than climate technology innovators in the average in this group of countries (Cleantech Group, 2021). In fact, based on the World Bank data, all research and development in Aotearoa New Zealand receives a lower level of investment than in other OECD countries, 1.47% of GDP, compared to the OECD average of 3.02% (World Bank, 2025a), and when paired with country’s proportionally low GDP (World Bank, 2025a), results in an overall low level of investment into research and development. In terms of climate technology innovation, generally transportation and energy innovators receive more investment than agriculture and resource innovation, which is Aotearoa New Zealand’s specialty. Israel, Finland, and Sweden, however, also share industry focus on agriculture and resources and still “*outpaced NZ’s amount of financing by wide margins”* (Cleantech Group, 2021)

Research acknowledges the need to spur both “horizontal” connections between niche actors (e.g. researchers, entrepreneurs) to foster invention, and “vertical” connections between niche actors and regime actors (e.g. business executives) to achieve sustainable transition. Additionally, there are two complimenting categories of policies that encourage innovation: “push” policies which encourage funding for R&D of new solutions even if there is no clear market, and “pull” policies that incentivize risk-taking and investment in new solutions, such as through tax incentives (Auerswald & Branscomb, 2003). “Push” policies for bio-materials are mandates for procurement, investment, and R&D, such as France’s RE2020 law that awards public contracts to firms that meet the mandates for 50% of building materials to be wood or bio-based (MTEH, 2024). “Pull” policies for bio-materials incentivise risk-taking and investment in new solutions, such as carbon and landfill taxes which financially incentivise use of low-carbon circular materials. One example of “pull” policies is New Zealand’s mandatory climate-related disclosures for large financial market participants, which aims to ensure the effects of climate change are routinely considered, demonstration of climate responsibility and foresight, and smooth transition to lower carbon economies (MfE, 2023).

2.5. Existing studies on perception of bio-materials

Two recent research exhibitions in Aotearoa New Zealand examined responses to hands-on experiences of bio-materials for built environment using examples of mycelium biocomposites and hempcrete (Walker, 2022; Murray, 2024). Both studies attracted higher response rates than expected, suggesting that there is a true interest to learn more about these materials.

The mycelium biocomposites research captured a strong association between mycelium and mushrooms and fungi with 87% of the 69 respondents reporting association with one of the two (Walker, 2022). The participants were asked to compare mycelium biocomposite samples with samples of more conventional interior building materials, and half of the respondents (50%) preferred lab-grown mycelium biocomposites, a waste-based bio-material, to other sustainable finishing, acoustic, and insulation materials, and 69% said they would specify or buy this material (Walker, 2022). However, the participants also reported concerns for aesthetic variability and atypicality, maintenance, durability, water-absorption, and health and safety (Walker, 2022).

The hempcrete research captured enduing stigma around hemp, with 38% of the 93 participants noting marijuana as their first association with hemp (Murray, 2024). This study asked for before and after rating of the same architectural solutions and captured an overwhelming shift for preference for hempcrete after exposure to more information about it and actual material samples, resulting in a total of 88% of participants reporting a change in their views on hemp and hempcrete after visiting the exhibition. More than half (55%) of participants responded that they were surprised when learning about the carbon emissions throughout the lifecycle of hempcrete (Murray, 2024), suggesting that more education on hempcrete might be needed in Aotearoa New Zealand.

Both studies were completed by Master of Architecture (Professional) candidates at Wellington School of Architecture, Te Herenga Waka – Victoria University of Wellington, and spaces within the campus were used for the research exhibitions. Although in both cases, other students in the School represented the most pronounced group of respondents, a high number of professionals and interested general public also appeared in the sample (Walker, 2022; Murray, 2024).

Other existing research has also shown specific dynamics which need navigating when dealing with increased adoption of bio-materials in the built environment. It has been observed that the perception of functional risk can affect consumer’s willingness-to-pay for products with reused or recycled content, disgust perceptions of atypical natural products can also affect consumer’s willingness-to-pay for bio-based premiums, although this appears to be positively mediated by perceived naturalness, health, and visual appeal (Hamzaoui Essoussi & Linton, 2010; Powell et al., 2019).

Jointly these studies show importance of hand-on experience with bio-materials which are not part of common current building practices, and that there is interest in learning of that nature. However, stigma, negative perceptions of irregularity in materials might discourage uptake.

3. Methodology

This study is based on a set of interviews, and in this section the methods used to collect, analyse and interpret data are explained.

3.1. Study and sample design

In order to understand the views of those involved with bio-materials, a series of semi-structured interviews were undertaken. This research has been approved by the Te Herenga Waka—Victoria University of Wellington Human Ethics Committee, reference number 0000031168. The interview questions were broadly grouped into four main groups of questions, asking about motivations, knowledge, attitudes, and settings. Those were complemented by a set of introductory and concluding questions recording information about the participants, and offering space to discuss cultural, social and similar considerations.

Participants were identified through a combination of representative and convenience sampling strategies. Because many bio-materials are in very early stages of development, the sample was skewed to include predominantly those who knew more about these innovative materials. Other research has demonstrated challenges when examining views of people with limited level of knowledge about the subject (Petrović, et al., 2016: Petrović, 2014), and therefore, this study focused on obtaining more input from those who knew more about bio-materials. The research team collaborated in preparing an initial list of about 50 potential participants mainly of the professionals who are already recognised for their work with bio-materials. During the interviews, this list gradually expanded to almost 100 possible interviewees. The potential participants were identified in an effort to represent as many bio-materials as possible, because it was conceivable that progress with adoption of different materials might follow different patterns which would be useful to evaluate. This was complemented by a reasonably full range of stakeholders which commonly engage with building materials. The range included: material innovators, manufacturers, architects and other designers, material researchers, policy makers, builders and others. Some of the potential participants had a long professional career behind them, while others were postgraduate students or recent graduates. Although, Aotearoa New Zealand based participants dominated the list, some important international leaders in the world of bio-materials innovation were also included. In the attempt to capture the most up to date insights in the area, participants included interviewees who have developed some of the most established innovative bio-based materials in the world, but also some who succeeded to start a business in this space, only to have to close it due to challenges with scaling up the innovation.

A total of 35 interviews was completed between September and December of 2023. 34 interviews were completed as video calls, which were recorded and transcribed, and 1 was submitted as a partial written response. Three members of the research team were the interviewers using the same set of questions in a semi-structured interview format.

Of the completed interviews, almost half of the participants were material innovators material/product designers, several were architectural practitioners, another several were academics in architecture or other material innovation related disciplines, and the remainder represented other relevant groups of stakeholders. Mycelium biocomposites and hempcrete were best represented newer bio-materials, while wool and straw were best represented more established materials. This was complemented by a range of other novel materials, such as seaweed and fish scales, and inclusion of some representation of timber-based products. This ensured that a broad range of bio-materials were included, and retained the focus of the study on those involved in niche innovation with bio-materials, while also providing a cross section through the industry as a whole.

3.2. Reflexive thematic analysis

A team of three research team members undertook the task of coding. A series of steps and strategies were used to ensure consistency of coding across the team. First two researchers coded one interview each, and independently developed a set of codes. Then those were discussed, reviewed and consolidated. This process was repeated and smaller and then larger batches, of parallel independent coding followed by discussion, review and consolidation. A third researcher was introduced through one of those stages. Through the process, a hierarchy of codes emerged as a strategy to capture more than one meaning or sentiment of the same statement. To ensure accuracy and consistency between coders, a glossary of codes was created, and expanded during the initial phases of coding. While some of the initial coding and the glossary used Excel, the main coding was completed using NVivo, a qualitative data analysis software suited to the requirements of thematic analysis (Dhakal, 2022).

A reflexive thematic analysis was undertaken, to understand key themes in the data (Braun & Clarke, 2021; Braun & Clarke, 2019). Thematic analysis is a qualitative research method developed by Virginia Braun and Victoria Clarke (2006), as an approach to analysing patterns of meaning in data sets (such as interview transcripts). A reflexive approach is taken to thematic analysis in this study, meaning that the researchers' interpretation of the data is acknowledged in the development of the themes (Byrne, 2022). In the words of Braun & Clarke (2019, p. 594), reflexive thematic analysis centres around "the researcher's reflective and thoughtful engagement with their data and their reflexive and thoughtful engagement with the analytic process". The analysis process in thematic analysis begins with coding data extracts based on the ideas or meanings presented. Key concepts are identified, which become central organising concepts for themes. Codes are then clustered based on shared patterns of meaning, acting as candidate themes. The themes are then iteratively and reflexively developed until they are appropriately refined (Braun & Clarke, 2021).

These codes were then reflexively organised and reorganised into clusters based on shared meanings (Braun & Clarke, 2021), which subsequently evolved into the refined themes presented in this report. The process of theme development and refinement was then undertaken by one researcher, to ensure consistency in the process. Given the size and complexity of the dataset, the selected themes in this text are the most prominent and high-level themes. Through this process 21 significant subthemes were identified which captured what was commonly found and shared by many participants in the data set, establishing the pronounced themes overall.

Those subthemes where then reorganised and to an extent reshaped into groupings of drivers, barriers, and enablers to more directly respond to the purpose of this report, resulting in the 19 final subthemes. During this process of reorganisation of subthemes, some subthemes were grouped, while others where split. In some cases, individual quotes or small sections of discussion were moved to another theme to ensure better alignment, but to a large extent the initial groupings still form the basis for the final themes.

3.3. Analysis of suggested actions

Throughout the development of the reflexive thematic analysis, emphasis has been placed on identifying actionable opportunities to address uptake barriers and drivers for bio-based construction materials. However, due to the nature of analysis, which favoured high-level themes, as the themes started to emerge, it became obvious that the results aligned with the original assumptions of the research team without providing a more detailed insight. However, that insight was evident in the data. Therefore, an analysis of suggested action was developed in parallel to the reflexive thematic analysis, but by a different member of the research team.

The first stage of categorisation involved codes being sorted into emerging inductive themes, representing areas of influence (leverage points): policy and regulations; knowledge and sharing; design and fabrication; and scaling innovation. From this point, sorting of codes focused on change actions solely. Sub-themes emerged representing actionable mediums for change (e.g., framework development, marketing strategies). A summary table was developed for each theme, and participant response frequency, ensuring that even outlier perspectives were highlighted. In order to provide clear goals for change makers to refer to, the table summarises the codes as change actions by referring to recommendations for developing SMART goals (specific, measurable, assignable, realistic, and time-related) (Doran, 1981).

The second stage of categorisation aimed to highlight for changemakers the different types of actions that generate change: change, certify, collaborate, create and customize. Inspired by MBIE's strategy report, the categorised actions are alliterated to aid recall, retention, and linking of concepts (Davis et al., 2015; Egan et al., 2020; Green, 2022). In the previous stage of categorisation, change actions were sorted by areas of influence in which change makers are often in similar circles sharing skillsets and influence. This new stage of categorisation transcends areas of influence and focuses instead on the types of change actions change makers will need to conduct. In addition to this categorisation of change type, change actions were categorised as either levers – direct interventions e.g. policies – or enablers – indirect support mechanisms e.g. education).

The third stage of categorisation aimed to conceptualise the ambition levels of change actions for systemic uptake of bio-materials in construction by visually mapping each change action to the previous three categories (1) area of influence (leverage point); (2) type of change; (3) type of impact; and a new category, (4) level of ambition. The resulting diagram enables change makers to select change actions to invest and instigate based on their available skillsets, resources, networks, and interests. A framework was developed to consider the complexity and impact of each of the change actions and assess their ambition level. A five-point evaluation scale was used for four criteria: (1) the maturity and availability of the change action subject (e.g. durable biobased coating or industrial hemp regulations); (2) the effort or dependencies of the change action method (e.g. workshops or updating of standards); (3) the availability and accessibility of the change action's network of actors (e.g. action requires a single actor or a multi-disciplinary network).

4. Thematic analysis results and discussion

The interviews covered a very broad range of topics. Those were grouped into drivers, barriers and enablers.

Some high-level issues included participants' recognition that there are no clear definitions for bio-materials. They expressed a similar range of views as discussed in Section 1.1. that bio-materials are a really broad group including many things that can be called bio-materials. Some expressed frustration with the term "bio-materials" and had a clear personal preference to use of other terms. Although the interviews were not set up to investigate what is the most appropriate terminology here, this data set indicates that possibly "bio-based materials" was a more preferred terminology. "Natural materials" were also often brought up during the interviews as an equivalent to "bio-materials" and "bio-based materials," and this was especially the case for those involved with traditional, natural materials such as straw and wool. This lack of definition was noted as contributing to possible confusion and miscommunication, and some participants reported that they often found themselves in a position of needing to explain such things. Therefore, the subsequent analysis, continued using terms "bio-materials," "bio-based materials," and "natural materials" interchangeably.

4.1. Drivers

The drivers that emerged align well with the context set out at the start of the report, by signalling three straightforward drivers. Participants reported that "there seems to be genuine interest," "people want more bio-materials," and there is a "demand from customers." This was further examined, and three key driver subthemes emerged: preference for natural and bio-based; growing interest in bio-materials; and client demand for bio-materials.

Driver 1: Preference for natural and bio-based

Participants discussed interest in bio-materials as closely related to the general preference for natural materials and the emotional benefits from those:

> *"You feel really good in that space, I think there is a sense of well-being that comes from being in spaces made with bio-materials."*
>
> *"[That building] prioritised natural materials where possible and one of the things that people note is that it just feels really good."*
>
> *"Ensuring that people have healthy homes and textiles that form part of [an] ecosystem of warmth and security.*
>
> *"We go inside a building that lets you see the wood and we always feel a bit warmer and nicer."*

Some participants offered potential explanations for this interest in bio-materials:

> *"We [people] are biological [... which] is why people react the way they do to timber and things."*
>
> *"There is that mental well-being side [of bio-materials] that you can get through mood reporting surveys."*
>
> *"We want to bring nature to the people without harming the planet, and it is just a proven fact that we, as human beings, have nature in our DNA, and we simply need it. [...] We need nature not only to relax, but also to be concentrated and focused, and to get our batteries charged."*
>
> *"The way for people [to learn to] trust physical materials is to let them handle them and see how they work."*

Interviewees recognised the sensory experience of bio-materials as an important aspect of this preference:

> *"For us it is important to keep the natural surfaces as natural as they are so you can only benefit from the natural looks, but also from the feel and the smell."*
>
> *"[A bio-material has a] texture to it and that is really important [for] being able to connect to nature."*
>
> *"We worked with multiple designers around this material and they are really excited over the new texture and new feel a and new concept."*
>
> *"I would love to see bio-materials start to be like more [of a] feature in spaces. I think that is a good place to start, [so] people can go and like touch it and be around it."*
>
> *"Expose them [bio-materials] or put them in place where you can touch them or smell."*
>
> *"I was really surprised when I started doing large scale PLA [3D] printing that the biggest response [...] was that my workshop smelled like waffles. It truly fundamentally transforms how you work with materials and how you feel about it. Literally, I almost turned my machine on as a perfume machine, it just is so beautiful to work with."*

Expanding on the above, some participants provided specific examples of how these sensory experiences can influence and benefit people.

> *"We live in environments with hard surfaces, hard painted walls, concrete floors, [and there is] a lot of acoustic noise all the time. But when you walk into a hempcrete house or a house that has been designed for acoustics and for even wall temperature, that feels like a passive house design. It completely changes your demeanour, your stress levels."*
>
> *"We pushed for timber, and it came at a slight premium cost, but the end result was really good. [...] We knew that we had to get that connection to nature, if we do not have that then it becomes a very sterile, very institutional place."*
>
> *"I definitely think it is all about that natural aspect, [...] it is all about bringing nature indoors. We spend too much of our time indoors."*
>
> *"I just I am very conscious that there is risk that we get further and further away from nature."*

Other planetary and social benefits were also noted:

> *One of the things that interest me in particular is thinking about materials the same way that our thinking around energy has developed. Bio-materials have a particular opportunity to be regenerative because they can sequester carbon [...], they are inherently grown [...] and you can consciously manage [to grow them] more sustainably whereas mining is never going to be sustainable. [...] The conscious management of material creation enables you to actually do things socially regeneratively as well, because you are designing the process not just the product.*

Driver 1 captures participant shared reports about general preference for and psychophysiological benefits of the natural and bio-based materials. They linked interest in bio-materials to a boarded preference for natural materials, highlighting their emotional and psychological benefits. Sensory experiences of touch, smell and texture were identified as key influencing factor for positive user responses. Such characteristics were recognised as an important driver for engaging with bio-materials and for their uptake. Preference for bio-materials was often brought up together with the mentioning of direct personal experience with bio-materials, and how that feels. This suggests that a direct personal experience is critical not only to obtain the psychophysiological benefits from bio-materials, but also to understand and learn about them. The emphasis on direct personal experience of bio-materials as the main driver for their uptake suggests that experiential learning might be important for growing uptake. However, currently, that sits in contrast with the audio-visual focus of most contemporary educational approaches.

Driver 2: Growing interest in bio-materials

Interviewees reported a general increase in interest in bio-materials from a range of groups throughout industry and beyond:

> *"We are seeing a trajectory that is starting to look really exciting for us as a manufacturer and a supplier to the industry"*
>
> *"There seems to be a bit of a groundswell [of interest in bio-materials] outside of just those with alternative lifestyles, a real attractiveness of using more nature-based materials."*
>
> *"Ten years ago, people were laughing at us because of our very natural, free spirits […] Now, there is a big demand popping up, and nowadays our stand is always the busiest [at material exhibitions]."*
>
> *"I believe that there is enough motivation and commitment in the industry and the customer to see that happen."*
>
> *"I think we are going to see it [scaling up of uptake of bio-materials] happen more and more in New Zealand."*

Similarly, to Driver 1, Driver 2 is also well aligned with the context set out at the start of the report, and the interviewees recognised that there is an intense and reasonably recent growth in interest in bio-materials, which can be seen as signalling a shift to a greater uptake. The interviewees reported a growing interest in bio-materials across a broad spectrum of stakeholders within and beyond the industry. This was presented as a shift from some of the past scepticism, and overall, the responses reflected a sense of optimism regarding the potential for continued growth and scaling of bio-materials uptake, and highlighted the increased mainstream appeal and demand.

Driver 3: Client demand for bio-materials

A number of interviewees identified clients as an important group driving interest and uptake of bio-materials:

> *"The demand is driven by customers. There is a demand from customers which is driving industry to change and innovate to keep ahead."*
>
> *"It is people's motivations and while I can offer some influence, I tend to think it is the client's motivations and influence really."*

> *"We have clients who come to us because they know that we [...] work with bio-based or lower carbon materials."*

Clients were also seen as an important enabler to help stimulate future change:

> *"Consumer demand is a great driver of change."*
>
> *"The end buyers to be demanding this, I think that would really help."*
>
> *"[One driver is] clients talking to other clients about their applications [...] and the benefits that they have felt from having the bio-materials in their building."*

Adding more specificity to discussion under Driver 2, the participants identified clients as a key driver of interest in and uptake of bio-materials. The interviewees emphasised the end users as influential actors in shaping material choices, sometimes even against the motivations of other industry stakeholders. Client advocacy and their sharing of positive experiences were seen as important contributors to accelerating adoption.

Conclusion on drivers

Taken together with the discussion at the start, it is possible to conclude that these results suggest that experiential learning about bio-materials is likely to be very effective in raising general awareness about their psychophysiological benefits and to drive uptake. The other important insight is that current sense of increase in interest in bio-materials creates an opportunity to build momentum to drive more accelerated uptake. Further to that, clients asking for bio-materials might be a really important driver, especially within business-as-usual scenarios, which is why a general increase in experiential learning about bio-materials might be the most effective way to truly drive greater uptake.

4.2. Barriers

While there are some real motivations and drivers for a greater uptake of bio-materials, some real barriers and challenges were also identified. The following subthemes emerged: lack of general knowledge about bio-materials; stigma and challenging perceptions; unfamiliarity is a challenge for the industry; cost inhibiting uptake; issues with scaling supply and production; resistance of the incumbent regimes; and issues with navigating greenwashing.

This analysis identified a greater number of barriers than drivers, including some apparent contradictions with the identified drivers. These tensions highlight the need for their resolution as a critical step toward the genuine acceleration of uptake.

Barrier 1: Lack of knowledge about bio-materials

Although client demand for bio-materials was recognised as a possible driver of uptake, interviewees also discussed that clients and other parts of the construction industry might not know enough in this area to effectively drive the change:

> *"In terms of clients specifically, I think it is really quite neutral, and in my experience, they do not know what that means. They have not had exposure to that word."*
>
> *"I think society at large does not know what is happening in this space, and when people get an opportunity to learn about it, they are incredibly supportive. People want alternatives."*
>
> *"Unless we are educating on the value given by the bio-based materials to the consumer, then they are not going to choose to use them."*
>
> *"Bio-materials are probably not on the forefront of people's minds in the industry apart from architects and designers, I think we all know what those are, but I do not think our clients do."*

The interviewees also noted that arriving to a client-led demand for bio-materials is not easy, because of the needed learning and unlearning:

> *"A lot of unlearning of what we are currently doing [is needed] to make space for that new way of doing."*
>
> *"There is a very big difference between bio-based and biodegradable, right? […] When we are doing our buildings, people sometimes come and [ask if] the buildings are just going to decay and we say: 'no, actually we are not doing biodegradable buildings.'"*

They also reported challenges were evident because we are in such early stages of adoption:

> *"I think we are still very much in the early stages of making bio-materials readily available for commercial use by clients, builders and the community at large."*

Despite some clients already driving uptake of bio-materials (Driver 3), Barrier 1 shows that a number of participants reported that many clients and general population seem to have limited of knowledge about these. Early stages of adoption and the need to unlearn aspects of the established practices emerged as the main explanations for this. This shows a real importance of providing a stronger knowledge infrastructure to support greater uptake of bio-materials in construction.

Barrier 2: Stigma and challenging perceptions

One area of significant agreement between participants was that care should be taken about stigma and other negative perceptions against bio-materials. These were reported to have a different level and nature of impact depending on the material in question. Stigma was particularly pronounced when it comes to hemp-based materials:

> *"When we were initially setting out, we got advice from a number of people not to mention hemp in any of our product names, to kind of steer clear of hemp because there is an association of it being related to cannabis."*
>
> *"I think there is a barrier in some sectors because of the associated culture that goes with it [hemp/cannabis]."*

Other bio-materials attracted responses signalling a range of other negative perceptions:

> *"When it comes to implementing mycelium materials into people's environments, people might be sceptical."*
>
> *"I think everyone in this industry still thinks that bio-materials are a risk."*

Some participants speculated that it might be possible to explain some of the stigma and negative perceptions by the inherent challenges of working with certain bio-materials:

> *"I have seen crumbly [poorly built] rammed earth [walls], [...] crumbling prematurely. [The challenge is that] rammed earth walls are not all tested. You can test samples, but you might have a whole section of walls that are done poorly and not know."*

Stigma and other negative perceptions appeared to still be common for some bio-materials and such participant sentiments were grouped into Barrier 2. Hemp emerged as stigmatised due to its association with cannabis, mycelium due to being unknown or associated with fungi, but also traditional bio-materials materials were seen as inferior and unreliable, because of their natural variability. This is another area important to address as part of support for greater uptake of bio-materials.

Barrier 3: Risk of the unknown is a challenge for the industry

Interviewees commonly mentioned that limited levels of experience and familiarity of architects, designers and contractors with bio-materials present challenges. Participants reported varying experiences with this, ranging from scepticism to outright resistance.

> *"[There is] a lack of confidence in the [bio-material] products because people are worried about the experience and the knowledge of the practitioner, and because these are not as commonly used materials."*

> *"The contractor may be very resistant because generally we are building with a 'design and build contract,' so contractor takes full liability for the building and any defects are their responsibility."*

> *"The quantity surveyor and the project manager are typically the people that will discourage you. […] The project manager will try and discourage anything that has a risk on it, that is not fully certified or tested or proven over the last 15 years. That is the difficulty with any material that has not had a long life, or comes from international sources."*

> *"There is a section of the market that say: 'we have been doing it this way for 40 years and this is how we are going to carry on doing it. It does not matter what you have or how flash it is, this is the way we do it.'"*

Contractors charging more due to unfamiliarity with bio-based products was commonly reported:

> *"Subcontractors refusing to use or pushing their costs up, saying: 'If you make us use those blocks, or those plasterboards, we are going to have to charge more because it takes us more time and we are going to have to waste [more] material.'"*

> *"People do not like stuff they are not used to, but if you get it into schools then by the time they get into industry they would be used to it. It is not a big change, it is just what they grew up with."*

Interviewees also speculated that the core issue might be limited availability of suppliers and installers:

> *"[It would also be helpful] if I can get two prices to have this particular material installed, so I know that it is pretty reasonable [product]. Or if I have a supplier who is happy to install as well, and they are going to back it [the product] up and provide a warranty and it has BRANZ appraisal, then I am pretty comfortable with that. I am still going to have to learn a bit about it, but I am not taking the risk on myself."*

However, participants involved with the development of new bio-materials, described a whole different type of unfamiliarity challenges:

> *"We did not know what this material would be like when something like that happens. [...] For example, our material is not heavy, so it is always going to float up. Another thing was shrinkage of about 5%. [...] We are fine-tuning and improving [this bio-material]."*

Barrier 2 brought together participant's reports that unfamiliarity with bio-materials is a challenge in construction industry. Interviewees mentioned a broad range of issues, from lack of confidence due to limited experience, to outright resistance to change practices away from what has been established for a long time. Risk of the unknown emerged as a theme that explains many of the reported examples: who in the industry should take the risk of the early applications of materials when nobody in the team has much experience with it? Design and Build Delivery Model was seen as pushing risk on the contractor, making them resistant to step outside of the reliability of using common and familiar materials and techniques. As a result, there were reports of some subcontractors refusing to use bio-materials or pushing their costs up to manage the risk. Even the participants involved with development of novel bio-materials acknowledged that they were still developing and improving their products, which signals their awareness of the room for improvement, and that this is a truly rapidly evolving field. Easier access to testing, third party appraisals, or manufacturer warranties were suggested as possible ways to decrease such risks due to unfamiliarity.

Barrier 4: Cost inhibiting uptake

The higher cost of bio-materials was reported as one significant uptake barrier, especially for clients.

> *"Generally, everybody wants more than they can afford. If we are suggesting that they use a bio-material and it will cost even more again, then that can be a deciding factor [for the build not to proceed]."*
>
> *"I think the current attitudes around sheep wool is that people love it, they love the idea of it. [...] If there was no other cheaper option, they would love to use it, and everybody would use it."*
>
> *"And it is such a mentality, for this is 'how I'm going to make my money?' and that is what is driving the homeowner. Do it cheap, do it quick and sell it for as much as you can. So, it is not built sustainably to last for generations. Where the money saving would be."*

Similar discussions about cost as a barrier were reported in relation to designers also:

> *"What I am finding with designers at the moment is [that] a lot of their projects, especially in the commercial and education space, are being driven by price. I was out seeing a big architectural firm today and they said 'look a lot of projects have been put on hold, a lot of them are going through really strict evaluations and products like the bio-materials are being pulled out.'"*

Participants commented on the complex relationship between the preference for the natural characteristics, cost of such materials vs. cheapness of the synthetic, petrochemical alternatives.

> *"People do choose materials for their biological characteristics and natural characteristics. But I think that is heavily influenced by price."*
>
> *"At the moment, all of the petrochemical products are going to outcompete by price the bio-based alternatives. For example, bio-based plastic might be anywhere from twice as expensive to ten times more expensive."*

Interviewees speculated that perception of cost might also be playing a role here:

> *"The perception of cost [also influences decisions] [...]. Think about going to a supermarket, and you go 'oh, if I buy organic food, it costs twice as much as nonorganic food.' Which it does. So, people assume 'oh wool is going to cost twice as much as the synthetic alternative', but it does not."*
>
> *"Bizarrely, biological materials are often viewed as being the most expensive."*

On the other hand, it was acknowledged that a higher market demand for bio-materials might be necessary for stable supply and decrease of prices:

> *"A stable supply of materials and systems to install [are needed] in order to get a reasonable price and to actually make this [greater uptake of bio-materials] happen."*
>
> *"Availability, having these products available for people to use, would just drive the market."*
>
> *"The risk with wool is that if the market share, the volumes, the value of the fibre does not grow enough, the sheep farmers will just move away from growing wool."*

These assumptions of the price drop with the scaling of production were also contested:

> *"If you can do it at scale, can people afford it? And then there is a whole different argument: if you cannot do it at the same price [...], is it still worth doing? Should people still pay a premium for it?"*

More challenging bulk procurement was also noted as a possible barrier associated with cost:

> *"The problem [...] in the industry is that actually contractors buy plasterboard at a much lower rate because they buy it in bulk. Whereas the alternatives they cannot buy in bulk. That really limits them on the bigger projects. I think that is going to be a key consideration in how to tap into the [bio-materials], and how to make that financially viable."*

Interviewees also discussed the need of financial incentives to stimulate uptake:

> *"I think there needs to be more connection with bio-materials and the banking systems, to help encourage consumers to look at using these sorts of products going forward."*
>
> *"I think there needs to be a mandate for adoption and a mandate in terms of investment. [...] almost making minimum requirements for the adoption of bio-materials or [a requirement that] in specific areas of building you have to use certain [bio]materials."*

Barrier 4 brough together participant reports that despite desirability of bio-materials, they appear to be expensive when compared to materials that currently dominate market, which presents a barrier for uptake. A series of existing industry settings were discussed as the likely factors contributing to this: current cheapness of petrochemical materials; economies of scale in manufacture of conventional materials; and practices developed by contractors and subcontractors to make gains and de-risk their work which assume conventional materials. Tendency of many in the industry to focus on lowering the upfront cost was also noted as contributing to this issue. However, some participants also speculated that there is an assumption, or perception, that bio-materials are more expensive, which might not be fully true. They also offered that with development of economies of scale, bio-materials would experience a reduction of any truly higher premiums. Underlying Barrier 4 is the question of how does the value of bio-materials truly compare to conventional materials which currently dominate market. This is especially important given that there is uncertainty on how such comparisons are to be made because many current retail prices do not capture all of the benefits and harm of materials.

Barrier 5: Issues with navigating greenwashing

Participants discussed issues with greenwashing, partial information and common misconceptions which can present barriers for more accelerated uptake, but also make conventional materials appear cheaper because of costs which are not discussed.

> *"[Getting] better informed about the cost of their competition [synthetic materials]. Being really honest about what those costs are: toxins, health issues for people working with them, or people living next to the [synthetic materials]."*
>
> *"Currently with green walls [what people see are] the plants which are green and bio-material, but all of these supporting structures usually are not. They can look very regenerative or environmentally friendly, but actually the products needed to build them are usually very heavy-duty plastics."*
>
> *"You can just dodge anything and say everything is environmental [...]. There are so many people that say their product is environmentally friendly and it is actually not. You can just go and get a certificate or say something, 'we recycle our products' or 'it is a take back'. But if you look into the take back, the take back is ridiculous, it is [often] not a take back."*

One example brought by the interviewees was timber which can be seen more favourably because of partial information on glues or chemical treatments commonly used on timber in construction:

> *"Thinking of all the cross-lam timber and all the other engineered timbers, [...] we still do not really know what is the impact of those. That is something I think we need to look at. [...] What is the impact of these timbers? What is the impact of the glues? We do not really know."*
>
> *"When people start telling me about working in timber, that irritates me: 'What do you mean, [working with] a toxic sponge?' They just do not get what you have to do to pine to make it durable."*

Some placed their trust in future standards and testing to resolve this:

> *"I would say there is a huge amount of greenwashing that goes on, but there are obviously entities and companies even in New Zealand that are trying to create standards and testing. And certainly, I think that is one way to ensure that people understand that your products really are sustainable, and [we] will be aiming to use something like that, but we are not really at that stage yet."*

Others acknowledged that to shift this much of unlearning will be needed:

> *"It is a bit of a journey, it is a bit of a process, and there is a lot of unlearning of what we are currently doing to make space for that new way of doing [things]."*

Barrier 5 grouped participants discussions of specific examples where partial information made products appear better than they truly are. In the participants' discussion on this theme there was a sense of a general agreement that greenwashing made bio-materials appear less desirable and more expensive compared with the conventional materials, especially compared to petrochemical industry. There is a sense of an uneven playing field because of the currently externalised impacts of more harmful industries.

Barrier 6: Issues with scaling supply and production

The discussions related to cost inhibiting uptake (Barrier 4) nicely lead into discussion of the barriers for production and supply of bio-materials. In Aotearoa New Zealand, this was commonly discussed by participants as a significant barrier:

> *"There are a few challenges for making that [greater uptake of bio-materials] happen. For me, at the core of the bioeconomy and generating new and different products is starting with the feedstock, it is getting the infrastructure in place to make new, and different products."*
>
> *"I think supply chains are becoming a bigger problem for us [in New Zealand]."*
>
> *"There is not enough supply or there is not enough supply of a valid product. And when it is available, it is obscenely expensive or it has many limitations..."*

Similar ideas to what was reported in relation to barriers for scaling uptake were reiterated:

> *"Unfortunately, if you do not have that large output the cost per unit is always going to be high for the greener material. This makes it harder for the adoption."*
>
> *"Bioeconomy is the big bottleneck for the current economy, because otherwise you are asking someone to say: 'okay, we have demonstrated that in the lab [how] I am going to build [...] this pilot plant and spend several million'. That is a big gamble for someone to do."*

Local manufacturers expressed similar views and their own focus on scaling up their manufacture:

> *"The petrochemical processes simply have the economies of scale that the new products do not have at the moment. As we start to scale up these processes the prices would become cheaper, [and] become more competitive. [...] But [that] will also need regulatory conditions to change."*
>
> *"We are focused entirely on mass production. How can you make this material at scale?"*

Participants also noted that investment might be needed to support scaling of production:

> *"New Zealand lacks this capability [for scaling up], and this is where, I think, investment is needed to help overcome [this challenge]."*

Manufacturers' investment in product certification and testing was also noted as a barrier for emerging smaller businesses:

> *"We just spent $15,000 just to get the product tested [in this country] again. And then we might have to do that again when the new version comes in. [...] It is just repetition."*

Participants from Europe also explained that similar financial incentives helped scale bio-materials production:

> *"If you start from the beginning, the collection and access to the raw material. In Europe, it was actually quite difficult because people were not used to doing that work for that specific resource. So, we had to create an incentive for them to do it."*

Nevertheless, this is also where general desire to do better was reinforced:

> *"People want to do the right thing, but if you do not get them infrastructure and resources, you are kind of wasting their time."*

Expanding upon the discussion about the importance of economy of scale under Barrier 4 to help reduce cost, under Barrier 6, participants discussed issues with this scaling supply and production. A number of interviewees expressed views that economy of scale can lead to a number of desirable solutions, however the supply of feedstock and other aspects of the needed infrastructure currently do not exist in New Zealand, which led some to wonder how could this scaling take place. Participants from Europe reported that in their experience incentivisation was needed to support similar transitions. Much of the discussion in this theme remained reasonably speculative, indicating that there is no tangible solutions which many see as the path forward for scaling supply and production of bio-materials.

Barrier 7: Resistance of the incumbent regimes

Resistance and existing power of the incumbent regimes were also discussed:

> *"Mainly it is interest groups like the dairy industry or fossil oil that [...] are preventing much more sustainable approaches."*
>
> *"We are finding that the likes of [large-scale building company] are entrenched in so many processes, including the development of standards that building materials have to pass."*
>
> *"Standards [...] force use of industrial products, rather than bio-based products."*

Challenges with shifting out of the status-quo of existing practices were also reported:

> *"The building industry is quite conservative in some ways. They do like staying with their particular product."*
>
> *"If you are a client looking at a residential build, the first person you generally talk to is the builder. And they are going to say: 'I do not know anything about that. We get our materials from Carters, or Bunnings, or Mitre 10,' or whatever."*

It was also recognised that the large incumbent producers were also better placed to develop new products:

> *"That is probably why [large-scale building company] have such a hold on the market, because they have the money to develop new products."*

Barrier 7 emerged as a theme of resistance of incumbent regimes to adopt a greater use of bio-materials. This was discussed as resistance and entrenchment of the large businesses in the industry, but also through the entrenchment of the construction industry as a whole.

Conclusion on barriers

This analysis has identified that despite genuine motivations and increasing interest in bio-materials, there is also a significant number and range of challenges to their wider uptake. These include limited knowledge, negative perceptions, unfamiliarity, cost, greenwashing, and structural issues and resistances within existing industry regimes. Overcoming these barriers is essential to support a meaningful and scalable transition to bio-based low-carbon material solutions.

4.3. Enablers

A range of possible enablers and levers were also discussed by the participants, and these are grouped into three groups reflecting the level at which they operate:

- Capability Enablers operate on the level of individuals, developing their own capabilities;
- Industry Enablers summarise the solution best deployed at the level of construction and building industry; and
- System Enablers capture system change possibilities.

In the group of Capacity Enabler themes, the key emphasis was on the importance of direct personal exposure to bio-materials as the key enabler of a broader uptake (Capability Enabler 1); built projects demonstrating the bio-material applications (Capability Enabler 2); and through workshops and similar educational intervention (Capability Enabler 3).

On the industry level, key possible support was identified in the use of simple drop-in solutions (Industry Enabler 1); professional guidelines and frameworks for bio-material applications (Industry Enabler 2); and through upskilling those involved with actual construction of buildings (Industry Enabler 3).

However, it is the System Enablers that group the discussion about possible more significant system-level changes: importance of long-term intergenerational approaches (System Enabler 1); regulative changes and other leadership government and ministries could offer (System Enabler 2); linking of the bio-materials with other industry trends, especially with EPDs and circular economy (System Enabler 3); and alternative ways for stimulating regime change (System Enabler 4).

Capability Enabler 1: Direct experience of bio-materials

Direct experience of bio-materials came through as one strong enabler of uptake for both non-experts and experts. For clients and general population this was primarily discussed as being about any exposure for the bio-materials:

> *"You have to experience [bio-materials], and then say: 'that is great, I want it in my place.'"*
>
> *"I feel like it would be impactful to just have more people interacting with the [bio-materials] on a regular basis to facilitate [a greater] uptake and trust with the material."*
>
> *"Have like a day where the public can come in and […] see and feel all these variety of things [bio-materials]."*
>
> *"The more of these types of buildings pop up, and people experience them and use and live in, I think that will also drive the trend to start moving into that space as well."*

However, for those in building industry the importance of hands-on aspect was especially emphasised.

> *"With bio-based matter there is a level of hands-on: you need to actually touch and feel, and do workshops, [in order] to really understand the positive impact [that material] can have."*
>
> *"The way [to get] people to trust physical materials is to let them handle them and see how they work and processes those."*

"You could read all of the documentation about the benefits and have all of that information available, but [it does not become real] until you have actually experienced it. And I think that goes for clients and consultants too. It really becomes real when you have experienced it and actually felt those effects yourself."

"You have […] be willing enough to understand the [bio-materials]. If you are not, then it is just something on a spreadsheet or some theory, you are never going to do it.

Some participants attributed this to be due to sensory and experiential qualities:

"I think that [touch] is a great way to make people more comfortable with things. If they can hold [the material] in their hands or have messed around with it, or got up to their armpits in mud and lime or straw or whatever."

Others recognised the potential for profound educational shifts through such direct experience with bio-materials.

"It is interesting that what we have seen with [for example] builders who are very quick to look at products like insulation and say, 'well, you know, it is going into a wall, we are sealing it in, it is not seen, it does not really matter what you put in there', to walking through our factory and seeing the processes and just connecting with the value added to the product. You know, going from a raw fibre that they are holding in their hands to watching the process through the other end, which is an insulation product. That is pretty fascinating to a lot of them and motivates [them to use] more of it."

The excitement generated as such events was also reported as a real motivator to continue working in this area:

"We have been in the market for a year now and one of the big things that sort of keeps you going through it is the positivity that we do get from people. Yes, it can be frustrating and annoying sometimes, but I find generally when I go out to the market that people really like the product and they really want to use it."

"While we were at that trade show, we came across an amazing natural product. To this day I still get as excited as I did the day when I first saw it."

Direct, hands-on experience with bio-materials emerged as a key capability enabler of their uptake, and it was seen as valued by both non-experts and professionals for fostering familiarity, trust, and interest. Participants reported that for clients and the general public, simply being exposed to bio-materials through buildings, events or tactile interactions was a powerful enabler of deeper engagement. Similarly, experiential learning was seen as important for shifting perceptions and encouraging adoption among professionals. Capability Enabler 1 emerged as the most important enabler of uptake overall.

Capability Enabler 2: Case study projects

Continuing with the importance of experience with bio-materials, participants recognised an important role of show homes, feature applications and other case studies to achieve the needed exposure, and transfer of knowledge of what can be done.

"Visiting people's homes is another inspiring or stimulating experience that encourages engagement."

"[It is good] if there is a way of showcasing the material, with its textures and stuff, [in order] to show the physical possibilities well. Hempcrete is a wonderful example of that: you can either have the very smooth finish, or […] more like straw [where] you can actually get to see the texture of the hurd."

"Some builder friends are bringing in some of natural building materials by incorporating them into existing buildings or in new builds as a feature. I think that could be a start for some people."

Those involved with promoting bio-materials also note using these strategies:

"We have a show home […] just to showcase the product."

"A question popping up regularly is: 'How can I use it?' And therefore, it is super important to us to inspire people. We need to get projects, or project images, that we can show to our customers to get them inspired."

Although others have questioned how widely is that dissemination reaching:

"There are some good [examples] out there, but I do not know if we are actually getting the experience widely disseminated."

Case studies were also signalled as a possible driver of uptake:

"What we need is a few examples that are consented and simple, and ideally that win a couple of awards, that kind of can pave the way for more of those projects to happen."

"Sometimes if you have a particular client that feels really strongly about something and the project is big enough […] you can kind of afford to push something and be innovative and get it certified and that can actually open the door for a lot of other projects and a lot of other use."

"If somebody [popular and famous] that everybody admires in the public world was to build something using these materials."

"I know academic papers are important, but honestly for the public and for most of the clients who will be paying to support these projects that is not where they look for information. Even practitioners, that is probably not where they look for information. So, I think actually like channelling media. Like there are many downsides to social media and stuff, but I think if it is used appropriately as a tool, it can be very powerful."

Case study projects, such as show homes or interior feature applications, were identified as central for increasing the uptake of bio-materials by providing tangible, real-world examples. Such views were grouped into a theme of Capability Enabler 2. Participants discussed the role of such examples in inspiring clients, demonstrating material potential, and facilitating knowledge transfer, but also in instilling credibility and building momentum for greater uptake. A need for a broader dissemination of such examples through media, awards, and high-profile project was also emphasised.

Capability Enabler 3: Semiformal education

In addition to experience and case study projects, a range of other educational interventions were also recognised by participants as useful enablers of greater uptake of bio-materials. For practitioners, participants discussed conferences, webinars and workshops as suitable for this education.

"[I got inspired when] I did some workshops with adobe, and also with working with light earth methods, […] and earth building types."

"Going to EBANZ conferences has been really inspiring."

"I think that the NZIA could have a stronger, […] more intentional way of providing their webinars. Rather than being a little bit of everything from the industry, […] every webinar [could be about] lowering the carbon emissions of the industry."

However, for clients, interviewees reported that clients often need to self-educate.

> *"I think there is an argument for people understanding what they are getting into, the results they are going to get. So really, people doing their research and engaging as much as possible with materials is going to lead to more positive outcomes and attitudes."*
>
> *"At the moment, I think it takes much enthusiasm on behalf of the client in order to make it happen, because there are many barriers and naysayers and uncertainty in the market."*

But also, that some support should be possible in this space:

> *"Unless we are educating the consumer on the value given by these bio-based materials, they are not going to choose to use them. We just have not done enough in New Zealand to educate the general public."*

However, for some the exposure to bio-materials was through a "chance encounter":

> *"It is a bit of luck too, because the conventional builders [that] I have encountered and who want to use new materials in their work, have all spoken about a chance encounter that they have had with some materials or some interesting building project."*

For some participants education about bio-materials was the area of specific focus and interest:

> *"I believe that if you can start to create an awareness, it creates a demand, and if you can create a demand, then businesses will try and meet that demand. That is really important."*
>
> *"I think [...] we definitely [want to] move forward with educating the wider industry as to what [sustainable materials] are, what are their benefits, and where to get them and [how to resolve the] supply chain issues."*

A greater connecting of these efforts was also signalled as needed:

> *"I think that there is a gap around a sort of more holistic voice. Because it is still quiet separated out by material type and it can be quite difficult to draw linkages between the different material types and the applications."*

Expanding upon this, the interviewees spoke about collaboration and partnerships as valuable approaches for driving positive change:

> *"Interdisciplinarity or interaction across disciplines has been an important focal point for allowing successful bio-material research – I feel a more flexible and a more interconnected network of researchers, designers, entrepreneurs even from different fields can increase the amount of work being done with bio-materials."*
>
> *"There should be partnering possibly with lots of people [and] I think it would be great if there was some sort of a government initiative."*
>
> *"What we do is [to] provide skills, not necessarily cash. That is part of the piece of around partnership as well. The partnership piece is the enabler."*
>
> *"[Collaborative] organizations are critical. [They can] enable greater facilitation of knowledge [transfer] between government, research and industry. [...] Awards and all other [activities can help] dissemination in industry."*
>
> *"What motivates me is this interdisciplinary environment, having different people with similar goals, but very different approaches [that] come together, and we can build something together. For me, that is always super motivating."*

In addition to direct experience and case study projects, participants identified a range of educational interventions as key enablers of bio-material uptake, and such discussions were grouped into a theme of Capability Enabler 3. The interviewees discussed hands-on workshops, conferences, and even webinars as effective to educational approaches for practitioners, and often suitable to enthusiastic clients. Importance of interdisciplinary and across sectors collaboration and partnerships was also emphasised as important for knowledge transfer and coordinated progress.

Industry Enabler 1: Ease of drop-in solutions

Within the building industry, participants discussed substitution of the conventional materials with bio-materials as the ‘low-hanging fruit’:

> *“[It would be great] if we can design a system that any qualified licensed building practitioner can integrate into a building by using the skill set that they already have.”*
>
> *“I think what is going to happen is that those materials are going to be forced to look more like conventional products.”*
>
> *“We recognized that if we took the polystyrene out of that panel and replaced it with a bio-material, we can have a similar performance ratio, but without all the nasties in it. And then keeping in trend with the construction industry, using it as a modular system, because people want houses quicker, faster, and cheaper.”*

Some participants also felt that the industry would force emerging bio-materials to conform to current practices:

> *“Innovators work hard to make bio-materials behave and conform to existing standards. But there might be other ways of being able to work with them, and other systems that would offer alternative ways of doing things. Currently it is hard to introduce an alternative approach and commercialize it when everything is determined by existing standards and standardized components.”*
>
> *“There is a lot of pressure on businesses to get the work done, make a profit, stay profitable, stay in business. If you want to do something [new], and it is all packaged up neatly, and we can fit it into our current work methodology, then yep, that is great, but if not, we will keep doing what we are doing already.”*

Interviewees involved with making bio-materials noted that they should also be working in this direction:

> *“[We, as people] who are trying to bring those bio-based materials into the mainstream, need to make sure that that we do it in a way that […] offers in an easy package for the industry to take on.”*

Standardization and prefabrication were discussed as similarly assisting with the ease of uptake:

> *“I think standardization is the key. If you cannot have a standardized product, that variation will lead to variation in your end product and output. And quite simply, it is not acceptable. […] Standardization [also] helps drive down costs, […] and [it is needed] from a regulatory perspective as well, because you need to meet certain performance criteria.”*
>
> *“A proven standardized system will always be easier [to use]. Because they have […] the documentation, they have a range of case studies, and use typically [they have] someone in the office or a contractor who has used it already.”*
>
> *“I am a great believer that prefabrication is the way to go here.”*

There was a broad agreement between participants of the real advantages of drop-in solutions, which offered substitution of conventional materials with bio-material alternatives within existing construction systems. This was seen as pragmatic and accessible entry point for the building industry, and are grouped into a theme of Industry Enabler 1. Many interviewees also recognised that bio-materials are more likely to gain industry acceptance if they aligned with current practices, standards and prefabrication systems, although, some raised concerns that such conformity could limit innovation and reinforce existing norms.

Industry Enabler 2: Role of guidelines in uptake of bio-materials

Interviewees discussed value of developing design guidelines and frameworks to foster uptake:

> *"The low hanging fruit for me [...] would be around really great and well adopted design frameworks. So, the considerations of bio-materials are built into the design process early on."*
>
> *"...how to create guidelines that could both be used for the designers, the people who are making the drawings to get consented, and [later] could be used by the consenting authorities. That would be quite amazing."*

An important subset of this was discussion of the types of applications suitable for bio-materials:

> *"We need to better understand and better identify [...] where and what are the best scenarios where we can efficiently apply bio-materials. [...] Thermal insulation was the first thing that came to my mind, because the material is confined, protected, not [very] exposed to external weather conditions, which may be an issue for bio-based materials."*
>
> *"I am quite sceptical of weatherproofing [...] and using bio-materials anywhere on the outside, [but there is value] of using them in living spaces and [where people are] close to the bio-material."*
>
> *"Because trying to get straw bales into the ceiling is pretty challenging, they use [other] products for the ceilings."*
>
> *"In terms of hemp and straw, I think [suitable uses could be in] prefabricated wall panels, [...] SIPs panels, [the] structurally insulated ones, or making boards."*

Better knowledge how to effectively use bio-materials in different regions was also mentioned:

> *"[It would be beneficial to have] a physical study of what kind of bio-materials should be used in what specific location or region, [to avoid] overlapping [with] another use."*

Desirability of smaller case study projects to drive uptake in industry also came through:

> *"Small companies want to start in an area they are confident with: they do not want to start with an entire building, they want to start with a pavilion or a small kiosk."*
>
> *"Builders [might] work with clients who perhaps are not ready to build an earth house, but they want to incorporate a heat sink, or might have an earth wall behind their fireplace."*

There was also discussion of who would be providing guidance in these areas:

> *"I do not expect this to come from the scientists/engineers only, instead designers must also write and share their scientific results and observations."*

Industry Enabler 2 brings together one important theme were participants discussing importance of developing design guidelines and frameworks to support the early inclusion of bio-materials into buildings. Such tools were seen as needed by a range of industry stakeholders, including designers, builders, but perhaps even more importantly by consenting authorities in order to create smoother regulatory pathways for bio-material applications.

Industry Enabler 3: Upskilling professionals

To support this grater uptake of bio-materials, education of professionals was mentioned as one significant enabler:

> *"The market is ready [for these products] but there is definitely a need for [more] education to be done, and it is being done."*
>
> *"[Currently,] there [seems to be] a lack of confidence in the products which more educated practitioners could overcome."*
>
> *"It is more the scale of change that is needed, and the number of people that are needed to help do a quality job. That is where the skills piece lies more when it comes to the green transition."*
>
> *"There is an opportunity for a bunch of sub-contractors to really train themselves up and be attractive for sustainable projects."*

Experiences with more established bio-materials also show this:

> *"What we have seen with wool is that [when] we are able to educate [people] enough, then the [same] risks are still there, but they are weighed up [and appear to be proportionally smaller]."*

Some disconnect was noted in the way new information on bio-materials is disseminated through built environment professions:

> *"Sharing the learnings directly with the people who need to absorb those."*
>
> *"Perhaps there should be [...] regulatory requirements around that in some way. [Different groups need to] talk to each other. It cannot be [done] in isolation. We cannot just worry about durability as separate from the carbon discussion."*

Educating young professionals and students across a range of disciplines was also mentioned as potentially useful strategy:

> *"We are going to start incorporating alternative building material piece into the actual process of them getting their apprenticeships to, just to try and break that cycle."*
>
> *"Start early with education, [...] all graduates leaving schools of architecture with a really good understanding of those bio-based and low carbon materials and that might change things."*

Unfortunately, a contradiction was also noted in the limited hands-on work in current tertiary education:

> *"We do not necessarily engage students with a whole lot of really hands-on material exploration, and consequently people go into professions without much exposure to the bio-materials."*

Education of professionals was identified as Industry Enabler 3. It grouped discussions about the needed activities to build confidence, skills, and a shared understanding how to work with bio-materials across the built environment sector. Two areas were identified as critical for shifting industry norms and supporting an enduring positive change: hands-on training of the existing practitioners, and education of students and apprentices, often also through hands-on experiential educational approaches.

System Enabler 1: Planning for long-term intergenerational approaches

Participants reported importance of using longer-term, intergenerational approaches on all levels:

> *"I think that there is definitely a need to build into the design process that we are not just building for end of life, but building for the next three or so iterations of the buildings. [...] Have a long term kind of view [...] beyond 50 or 100 years, so, that starts to become more of a te ao Māori piece where it is a more multigenerational [approach]."*
>
> *"It is hard, because when you are trying to explain to customers that maybe the materials cost [for bio-materials] might be a bit higher than building [with conventional materials] ... but the long-term costs are much less because you are saving in your heating, your cooling, and all that kind of performance stuff."*
>
> *"We need to be building that green New Zealand image and then we need to encourage the [successive] governments, [...] to realize the value of that image [ongoingly]."*

But also, that relatively temporary changes can have lasting negative impacts:

> *"In 2012, in the UK, the conservative government got rid of all of the green policies that were driving the construction industry towards zero carbon. I had been doing a lot of work around zero carbon, and [witnessed that] that whole industry just evaporated. People like me left and moved on to another sector and have never gone back. A lot of knowledge and experience gets lost when you lose that regulation."*

Participants discussed the importance of adopting long-term, intergenerational approaches in development of design and policy, highlighting the importance to consider cultural frameworks such as te ao Māori. They also warned that short-term policy reversal can cause lasting setbacks, leading to the loss of momentum and expertise.

System Enabler 2: Regulations and support from government and banks

Participants discussed the top-down changes in influential policy and regulation settings.

> *"I think the regulatory requirements are the biggest [thing] that is going to stimulate [the uptake]."*
>
> *"Most of the people [are] actually pushing the changes in terms of legislation, and I think they are coming at it from the right angle."*
>
> *"I think there is a role for government to play in facilitating these transitions. It would be interesting to understand what some of the strategies [would be], or what could be the role of government, what policies [...] could [...] affect adoption and uptake."*
>
> *"Maybe having norms and legislation being rethought based on the dynamic environment that we have right now for construction and depending on the use."*

Shortcomings of the current regulatory efforts were also discussed:

> *"Most regulations tend to lack a bit of nuance. They tend to put things into buckets of good or bad, while the world is not like that. For example, at the moment, recycling is [...] pushed in the polymer space. But there is a role for compostable materials as well. It is not one or the other. It is understanding that actually*

for different use cases, different end of life solutions are applicable. I think one of the biggest challenges that we have with the regulations is that they tend to lack such nuance."

"I think [MBIE] is far too focused on stopping bad things happening, as opposed to letting good things happen."

"Building code and building act [could] remove barriers, making bio-materials just as easy option to pick [as a conventional material] off the shelf."

But also, that such efforts that could be politicised:

"There are many […] aspects […] that are connected to politics, I mean, you see the way climate change is being politicised."

An alternative approach to regulatory initiatives was mentioned by several participants who specifically cited the EBANZ earth-building standards as an example of a regulatory change driven by the industry:

"Things like the earth building standards are great and I know that they have been done by a group of passionate people and that took a long time."

"I think the work that has been done on the earth building standards in New Zealand is pretty impressive. And if we had a hemp building standard, or a standard applied to some of the other [bio]materials […], then that would be really useful."

Other potential forms of top-down leadership were also discussed:

"[It] would help us [if there was more of regulatory initiatives] similar to what the [Ministry of Education] has put out: mandating more of bio-materials […] used in the building industry."

"[In such initiatives] if [the building designers] are not choosing the lowest carbon option, they have to provide the reasoning why they are not doing that. This is a good move, I think."

"I do not believe that it would take that much to start seeing some real momentum build with bio-based products, but it needs it needs to come from a higher level."

"There are ways for the government to […] say: 'well, we will do this testing because we know it is going to develop an industry in New Zealand and in the long-term we are going to get tax returns from that industry.'"

Interviewees also discussed financial incentives which could help in more than one way:

"I think there needs to be more connection with bio-materials and the banking systems, to help encourage consumers to look at using these sorts of products going forward."

"I think there needs to be a mandate for adoption and a mandate in terms of investment."

The participants discussed opportunities of top-down leadership through regulatory and policy interventions for accelerating uptake of bio-materials, and these and similar discussions were brough together in the theme of System Enabler 2. These discussions recognised the role of the government leadership in facilitating transition and setting clear mandates, although the role of banks and investment systems was also seen as important.

System Enabler 3: Linking bio-materials uptake with other industry trends

Interviewees recognised the low-carbon initiatives as one potentially strong driver for a shift to bio-materials:

> *"One of the most convincing arguments for stimulating the uptake of bio-based materials [is their low-carbon aspect]. Since now we have a growing interest from the government towards net-zero carbon calculation, and the embodied carbon calculation of buildings will become mandatory in the near future."*
>
> *"When the building code requires you to measure embodied carbon, that flows through the market so the manufacturers are increasingly providing EPDs. Most bio-materials will have a very good result and that would give them a leg up to be used in more projects, especially for projects that are trying to meet particular lower carbon targets."*
>
> *"If we use that carbon budgeting approach, we can see that bio-materials have a positive effect on the carbon footprint."*

Some also noted that such initiatives could help expand the focus from prioritising the operational energy:

> *"I have friends who are really right into Passivhaus or high-performance houses, who know that the next level that they are not really covering is the embodied carbon in the building materials that they are using."*

Efforts towards circular economy were also recognised as complementing the low-carbon efforts:

> *"In my view, a way to get there would be to integrate it [bio-materials] into something like Greenstar, and make sure you have EPDs [for those materials]."*
>
> *"To actually […] try to [achieve] circular economy, you need more bio-based materials."*
>
> *"It will be great in a circular economy approach to have more bio-based materials […] in our construction processes."*
>
> *"I think you need the complete a circular analysis to go 'yeah, if we scale this up, we actually have a big solution, not a big problem.'"*

However, high cost of EPDs were also noted as an obstacle for smaller or emerging material developers:

> *"You got this R&D [research and development] and you are going to have to do an EPD and invariably what I am hearing is every time you change the material in your product, you have to redo an EPD. So, you really want to do affirmative R&D first before you even think about the EPD."*
>
> *"Most people do not realise the cost involved in bringing a unique material […] into the building industry […]. That is the biggest deterrent. […] For example, doing EPDs, is a really expensive process. Obviously, that is nothing […] for a big company. But for the smaller companies that do not have EPDs yet, […] it is a big commitment when they are just trying to get their product out onto the market successfully."*

Besides the cost of EPDs, some participants also reported concerns with variation in methodologies creating a need to do multiple EPDs:

> *"On the other hand, there is no standardised [EPD] method even here in Europe. The French are doing [EPDs] in a different way than the Germans, Austrians, and Norwegians. And now, we just want to have it. We want to have the lifecycle assessment. We want to have something in our hands. And then we just*

started now, and it is for us a bloody investment. I mean, it costs a fortune. It costs a lot of time and effort. And eventually we do not know if we have the real deal in 12 months' time."

Participants also noted other complexities for both determining and using those measures:

"People need to understand much more about lifecycle analysis (LCA), because determining how sustainable things are is complicated and difficult."

"One big problem with some of those amazing analytical systems, like LCAs and EPDs, is that they are complex and hard for people to understand. Where do designers go to find useful and accessible information? Currently the information is not very navigable for people."

Participant discussions of low-carbon initiatives, EPDs and similar current industry trends were grouped into the theme of System Enabler 3. Embodied carbon was seen as a potential strong driver for increasing the uptake of bio-materials, given their generally favourable performance. Additionally, interviewees highlighted the complexity of LCA and the need for more accessible and standardised data to support designers and practitioners in more effectively adopting sustainable materials.

Conclusion on Enablers

Enablers present the largest number of themes that emerges, which were grouped into three sets of three themes each, and discussed here in groups.

Capacity Enablers

Through all three Capacity Enablers, importance of direct experience with bio-materials, re-emerged, reflecting the discussions around Driver 1. This group of themes focused on the level of individual or grassroots signalling that people as individuals, or in small groups, can enable change through their own upskilling and upskilling of those around them. This in turn creates capacity for greater use of bio-materials throughout the industry. Capacity Enablers complement each other by exploring different facets of the importance of direct personal experience and education about bio-materials, and are grouped around the focus on giving people direct experiences with bio-materials (Capacity Enabler 1), showing bio-materials through case study projects, even if that is just a feature wall within an existing building (Capacity Enabler 2), and asserting relevance of semiformal education about bio-materials (Capacity Enabler 3). This set of enablers can also be seen as resolving some of the issues raised in Barriers 1-3: lack of knowledge (Barrier 1), stigma and other challenging perceptions of bio-materials (Barrier 2), and issues with unfamiliarity (Barrier 3) can be at least partly resolved through direct hands-on experiences with bio-materials, case study projects, or learning more about them.

Capacity Enabler 3 groups responses which discussed existing semiformal education which can range from chance encounters to reasonably formal education available through voluntary niche interest groups. Figures 1 and 2 show exhibitions which operate as Capacity Enablers 3. These are very effective to support already somewhat interested individuals to develop their capacity to work with bio-materials. Participants also spoke about the importance of interdisciplinary collaboration not only in order to achieve the needed bioeconomy development, but also as the motivator, with some interviewees suggesting that niche organisations should be formed to help facilitate collaboration of this nature. Unfortunately, a limitation of developments within niches is that all efforts could remain within the niche for a long time, which is why for a greater uptake throughout industry other enablers are also needed.

Industry Enablers

Industry Enablers bring together responses discussing solutions or interventions which could support a greater uptake of bio-materials in construction and building industry. Industry Enabler 1 emerged as one strong theme in responses discussing introductions of bio-materials as “drop-in” solutions, directly replacing some of the materials that are already on the market or piggybacking onto already existing industry trends like the move to prefabrication. This enabler can be seen as closest to business-as-usual introduction of bio-materials, and some bio-based materials, such as wool insulation bats, already operate as interchangeable with other insulation bats, ready to be “dropped-in.” Interest in prefabrication has led to development of Structural Insulated Panels (SIP), and some bio-materials, such as hempcrete or straw (Figure 1), are already being offered in this way, piggybacking on this industry trend. While solutions of this nature are welcomed and should continue, they might require mixing of the natural materials with less natural components (e.g., polyester in the wool insulation bats, and treated timber in straw SIPs). Rather than leading to a system change, “drop-in” solutions fully put pressure on the bio-based newcomer to fit within the existing systems, effectively operating within the business-as-usual. Also, “drop-in” applications are unlikely to be suitable for all available bio-materials.

Industry Enabler 2 grouped responses which discussed role of professional guidelines in uptake of bio-materials. This enabler can be seen as another part of the solution for the Barriers 1-3 where lack of knowledge (Barrier 1), stigma (Barrier 2), and unfamiliarity (Barrier 3) were identified as challenges. In contrast to Capacity Enablers, which talk about what an individual or a small niche can achieve, Industry Enabler 2 emerged from responses which discussed importance of development of professional information, industry standards and guidelines how to work with bio-materials. A need for further professional guidelines was equally mentioned in relation to introduction of emerging bio-materials and for more effective and confident applications of the traditional bio-materials for contemporary needs. The responses identified a need for more knowledge for a range of areas: thermal performance of the bio-materials; required weatherproofing; details how to resolve more challenging applications; but also more knowledge about local availability of bio-based materials.

Broadly belonging to a group of interrelated themes that talk about the importance of more education about bio-materials, Industry Enabler 3 moves from the focus on individual experiences to more structured experiential training for the industry. The responses suggest that there is a need for groups of professionals, especially younger professionals, to be more educated about bio-materials during their training in order to bring the needed skills into the industry and help with addressing Barriers 1-3. The participants suggest that this should be hands-on experiential training on how to work and build with bio-materials. This is needed for a range of professions within the industry, not only designers and builders, who are critical, but also local council inspectors who should also know enough to enable uptake. The responses also signal that there is a strategic opportunity for those who upskill early in this area to became leaders, obtaining cutting edge benefits.

Industry Enablers 2 and 3 show that there is a potential to use professional guidelines, and upskilling of the professionals to stimulate greater uptake of bio-materials. While the professional guidelines capture scientific and potentially more abstract knowledge, the experiential training for the industry would bring hands-on knowledge how to execute those.

Once more is done to ensure progress with all three Industry Enablers, there would be much stronger infrastructure for a transition to bio-based construction. However, unfortunately, these do not achieve much of system change.

System Enablers

There are limitations of how much can be achieved by using the enablers discussed so far, because these operate on the levels of individual/small group or industry, and sit under the broader umbrella of sociotechnical and other systems which can inhibit or stimulate action. Participants also discussed these broader systems and suggested opportunities to stimulate change from those levels. Insights in these areas were grouped into System Enablers and present the most ambitious, slower but more profound system changes.

Discussions on the importance of long-term intergenerational approaches were grouped under System Enabler 1, and had more than one aspect to consider. The participants referred to long-term intergenerational approaches in a range of different ways. Some discussed the te ao Māori multigenerational approaches, which gives importance that buildings remain in use for multiple generations. Thus, in the context of Aotearoa New Zealand, te ao Māori multigenerational approaches could give an even stronger grounding for keeping buildings in use for longer. On a much more basic level, participants discussed importance of educating clients about longer term cost benefits from using bio-materials with excellent insulating properties, which talks about importance to shift away from upfront costs driving many decisions in construction, but rather considering the whole-of-life approaches to cost. An important remark from an international participant was that they are aware of examples of government policies changing to abandon certain pro-environmental initiatives, which later led to a significant loss of momentum and expertise, showing an example of short-sightedness which can be avoided through the more long-term view approaches. Jointly these show the cultural and practical importance of a sustained long-term view and that it is relevant to position greater adoption of bio-materials within this long-term intergenerational context. This enabler also provides some answers when cost inhabiting uptake is discussed (Barrier 4), but also could be significant in addressing aspects of resistance of incumbent regimes (Barrier 7).

A number of participants discussed the importance of regulations and other areas where government or banks could play a powerful role in leading top-down change. These were grouped into System Enabler 2. Regulatory requirements for inclusion of bio-materials were reported as a very important lever that could stimulate much greater uptake, and support growth of momentum, creating a path for addressing some of the issues with scaling supply and production (Barrier 6), and possibly lead to a decrease of cost of bio-materials (Barrier 4). Existing examples of requirements for inclusion of bio-materials were also discussed, showing, as discussed earlier, that there is a momentum in this space already, but also that much more could still be done within Aotearoa New Zealand.

However, participants also discussed other enabling the government could support. An example where regulations were developed by niche professionals was discussed as very challenging to achieve without government support or involvement. Regulations of that nature are needed for overcoming issues noted in a range of identified barriers, especially when considering lack of knowledge (Barrier 1), unfamiliarity (Barrier 3), and issues with navigating greenwashing (Barrier 5). Therefore, government's support of the production of the needed standards and regulations could have a very significant positive impact on enabling greater uptake of bio-materials.

A related facet of this, was a suggestion that government could simply support of testing of the novel bio-based products so that emerging bioeconomy manufacturers face fewer obstacles, thus directly stimulating growth of the local bioeconomy. This in itself would go a long way towards addressing the issues with stigma and challenging perceptions (Barrier 2) and issues with navigating greenwashing (Barrier 5) by providing authoritative and reliable information about emerging bio-materials. Similarly, a need for a connection with banking systems was also discussed as another top-down force that could have a beneficial impact, which could aid for financial removal of some of the obstacles which currently face bioeconomy. This discussion shows that there is a range of supportive top-down actions that could enable transition to bioeconomy.

System Enabler 3 grouped discussions which linked bio-materials with other industry trends, looking for possible synergies. This broad group included suggestions that the move to reporting embodied carbon will naturally lead to a greater uptake of bio-materials as the low-carbon options, but also that it would be possible to integrate stimulation of bioeconomy into other existing systems such as Greenstar or Passivhaus, just as circular economy concerns could lead to a greater uptake of bio-materials. Any of the existing industry trends could present very real system enablers for a greater uptake of bio-materials, and they have potential to help address most of the identified barriers. However, in such conversations EPDs emerge as the key tool used by many of the existing industry trends, and there was also much discussion about EPDs themselves. On one hand, many participants did talk about LCA and EPDs as very useful tools, but others also commented that there is no standardised EPD method which reduces reliability and comparability of results, which also means that material manufacturers need to prepare a number of costly EPD assessments, and regularly redo/update those. In addition, some commented that the both LCA and EPD results were challenging for the designers to easily follow and understand. From such discussions it is clear that while there are true opportunities to tap into such existing industry trends to stimulate uptake of bio-materials, there is also a range of obstacles especially given that the transition towards consolidated LCA and EPD data is still taking place.

Complicating things further, incumbent industry tends to have the funds to prepare EPDs and their regular reviews, and incumbent representatives are more likely to be included in the conversations when these tools are developed, than start-ups in bioeconomy. This can lead to EPDs contributing to greenwashing (Barrier 6) and bio-materials appearing less favourable in such assessments. Therefore, in order to support an equitable transition to carbon accounting, makers of bio-materials should to be able to take part in it and that might require government, or other public bodies, to provide some assistance to balance the playing field.

4.4. Conclusion of thematic analysis

Themes that emerged when examining drivers appear broadly in line with the dynamics introduced at the start of this report, but also enable some further insights because of the specificity of the individual stories and views of the interviewees. This thematic analysis identified a set of drivers, barriers and enablers. A greater number of barriers than drivers was identified and a strong number of enablers which can help greater uptake of bio-materials. Figure 8 visually summarises the identified drivers, barriers and enablers for uptake of bio-materials.

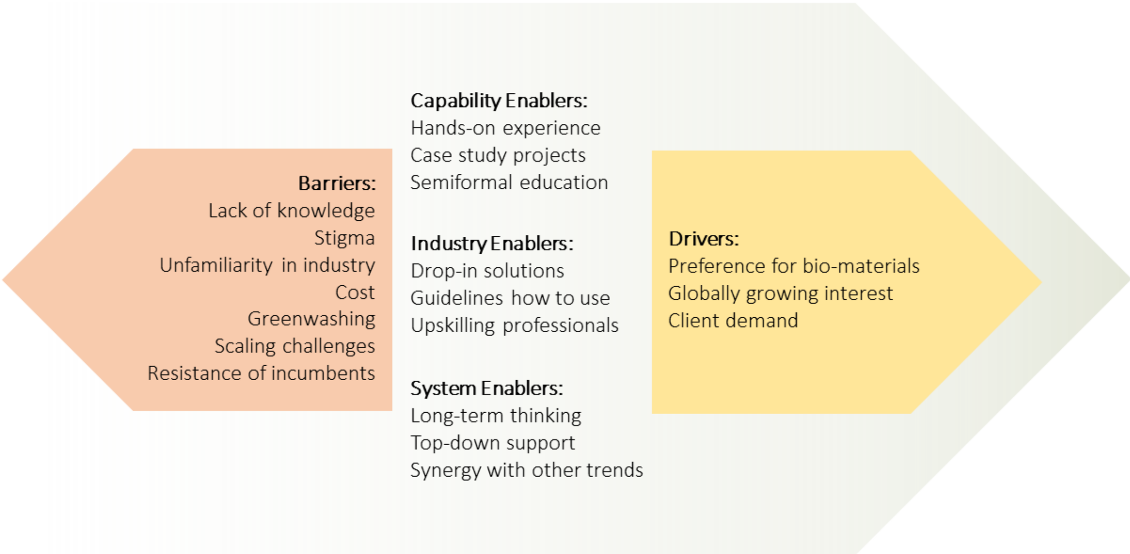


Figure 8: Summary of the identified drivers, barriers and enablers for the uptake of bio-materials.

The nature of typical thematic analyses is that they focus on the most common themes, capturing sentiments where there is a higher overlap between participants. Because of this inherent characteristic, it is to be expected that a thematic analysis would arrive to findings which are more commonly seen as reliable, but also might arrive to some of the confirmations of the what was already known. In this case, the identified drivers, barriers and enablers have some overlaps with the information available in the initial literature review in Section 2, although the results give a greater depth and clarity to some of that discussion. To compensate for that, within themes, an effort was made to include a reasonably broad range of views and in Section 5 additional analyses were undertaken.

5. Analysis of suggested actions

Following the thematic analysis, which identified the key high-level drivers, barriers and enablers for the greater uptake of bio-materials in construction, a further analysis was conducted to explore more specific suggested actions. Rather than focusing on examining what participants commonly said, the objective here was to use their responses to map out the widest possible range of views on what form actions might take and who should take those actions.

Given that both analyses worked with the same data from the interviews, there are some overlaps in findings, and some of the identified insights are the same or similar which confirms the reliability of findings. However, this subsequent analysis of suggested actions starts to map out the actual specific actions that could be taken to drive a broader shift to bioeconomy for the built environment, including identifying actors, and articulating operationalised findings.

The results of the suggested actions analysis are reported based around three separate layers of consideration. First, the areas of influence are introduced and the relevant actors/stakeholders; then categories of changemaking actions are discussed; and finally, the results from those inform the ambition level of change actions analysis, which can be used by any of the various actors in the industry to identify some actions suitable for their context to drive actual change.

5.1. Areas of influence and actors

The following sections organise the actions suggested by the interviewees into a set of suggested actions that can help a broader uptake of bio-materials in Aotearoa New Zealand construction or more broadly. These have been grouped into the four areas of influence: scaling innovation; design and fabrication; knowledge sharing; and policy and regulations. In addition, actors, stakeholders and other groups most suited for the particular area of influence are also discussed.

5.1.1. Scaling innovation

Scaling the innovation areas of influence emerged based on participants discussing the gap between developing an innovative material and getting it to mainstream markets. These change actions are most relevant to the actors and stakeholders such as start-ups, innovators, change organisations, and industry incumbents looking to support innovation. Table 5.1 shows key themes of change actions identified and recommended by participants for scaling the uptake of bio-materials for mainstream use. These are: market strategies; circular systems; target typologies; target clients; material experience; and strategic networks.

Table 5.1 Summary of actions for scaling innovation with the number of their appearances.

Sub-theme	Actions	Mentions (#)
Market strategies	Radical differentiation entry strategy e.g. temporal qualities	7
	Conforming standardisation entry strategy	5
	Target less regulated markets first e.g. packaging or finishes	3
	Import-based seeding strategy	3
Circular systems	Positioning bio-materials as coproduct of food system	6
	Digital management of stewardship and data	1
Target Typologies	Target residential and interior project	3
	Target applied finishes projects	3
	Target circular interior and retail fit-out	1
Target clients	Target enthusiastic, mission-driven early adopters	3
	Target large portfolio clients	1
Material experience	Employ material experience to shift perception	9
	Trade shows and showcases	2
	Hands-on workshops with architects & contractors	1
	Community building workshops	1
Strategic networks	Collaborations with direct competitors	1
	Material research ventures	1
	Equity-for-expertise partnerships	1
	Partnerships between start-ups & technical consultants	1
	Partnerships between start-ups & larger manufacturers	2
	Investment partnerships with contractors & designers	1

This shows that there is a number of actions that could be taken by those involved with the innovation and scaling of the uptake of bio-materials. The most frequently mentioned recommendations included employing material experiences to shift perception; adopting both radical differentiation; conforming standardisation strategies for market entry; positioning bio-materials as a co-product of the Aotearoa New Zealand's food and beverage system; employing material experiences to shift perceptions of bio-materials; initial import seeding strategies (e.g. importing before investing in local production); targeting mission-driven clients; and targeting interior and applied finish applications.

5.1.2. Design and fabrication

Design and fabrication area of influence emerged based on participants addressing opportunities to develop bio-materials to support their uptake. These change actions are most relevant to stakeholders such as material designers, design clients, and architectural design teams. Table 5.2 shows key themes of change actions identified and recommended by participants for bio-material design and fabrication. These are: circular design practices and design framework development.

Table 5.2 Summary of levers for design and fabrication with the number of their appearances

Sub-theme	Lever	Mentions (#)
Circular design	Circular fabrication systems	4
	End-of-life decomposition design	4

	Prefabrication to mitigate risk	2
	Bio-material design mindsets	4
	Bio-based coating e.g. PLA	2
Design frameworks	Bio-material preferring procurement processes	3
	Community-driven fungal design frameworks	2
	Engage young professionals in framework development	2
	Design frameworks adopted for bio-materials	1
	Integrated design processes to de-risk	1

This shows there is a number of actions that could be taken by those involved with design and fabrication of bio-materials. The most frequently mentioned recommendations included developing circular or prefabricated design systems to reduce waste and mitigate risk; adopting bio-material design mindsets; designing end-of-life decomposition of materials to be project or region specific; and establishing bio-material preferring procurement processes e.g., government procurement.

5.1.3. Knowledge sharing

Knowledge sharing area of influence emerged based on participants addressing opportunities to increase awareness and trust, develop skills, adopt holistic practices, and minimise misinformation through knowledge sharing. These change actions are applicable across many stakeholders: government, industry, education and start-ups, and across many disciplines: material science, architecture and design, engineering, and policy. Table 5.3 shows the key themes of change actions identified and recommended by participants for bio-material knowledge sharing. These are: upskilling; storytelling; and ecological symbiosis.

Table 5.3 Summary of levers for knowledge sharing with the number of their appearances

Sub-theme	Lever	Mentions (#)
Upskilling	Organise demos for installers	3
	Develop sub-contractor bio-based material training	2
	Develop core bio-based tertiary programs	1
	Practice active client education strategies	1
	Train early e.g. apprentice level	2
Storytelling	Host regular webinars (e.g. consenting, lessons learnt)	3
	Prioritize multi-disciplinary holistic voices	3
	Run workshops to create consenting guidelines	2
	Increase awards for dissemination	2
	Create listening environments for indigenous voices	2
	Generate educational content for social media	1
Ecological symbiosis	Conscious management of material production	2
	Consider wider social ecosystems of industries	2
	Understand material agency and mana	1
	Understand designer place in wider ecosystem	1
	Run biophilic design workshops	1
	Adopt biophilic frameworks e.g. Living Building Challenge	1

This shows that there is a range of actions that could be taken to achieve the sharing of knowledge on bio-materials. The most frequently mentioned recommendations included organising bio-based material demos and upskilling for installers and apprentices; hosting lessons learnt and consenting webinars and workshops; developing listening environments for multi-disciplinary, holistic, and indigenous voices; and facilitating cross-sector and cross-industry discussion e.g. food and beverage or textiles.

5.1.4. Policy and regulations

Policy and regulations area of influence emerged based on participants addressing opportunities for to stimulate the uptake of bio-materials in construction through regulatory approaches, including standards and building code. These change actions are most relevant to stakeholders such as policy makers, local government, standard developers, change organisations and lobbyists. Table 5.4 shows key themes of change actions identified and recommended by participants for bio-material-supporting policy and regulation. These are: regulations; policy; incentives; standards; and certification.

Table 5.4 Summary of levers for policy and regulation with the number of their appearances

Sub-theme	Lever	Mentions (#)
Regulation	Adopt regulation to support industrial hemp	4
	Develop commercial fungi regulation	3
	Adopt genetic engineering regulations	3
	Indigenous fungi licensing models	3
	Develop bio-based import data guidelines	2
	Regulate the term biodegradable	2
Policy	Invest in industrial composting system	3
	Encourage industrial symbiosis and waste reuse	1
Incentives	Mandate bio-materials for procurement	2
	Tax non-bio-materials	2
	Mandate bio-material investment and R&D	1
	Provide financial kickbacks for bio-material use	1
	Increase carbon taxes	1
	Increase landfill taxes	1
	Promote investing visa schemes	1
	Reflect cradle-to-cradle in costs	1
	Reflect planetary boundaries in costs	1
Standards	Adopt building code to allow bio-based innovation	3
	Develop risk matrices for standard exceptions	3
	Develop reuse standards and systems	2
	Develop cycles of maintenance	1
	Evolve biogenic carbon standards	1
Certification	Mandate support for bio-material certification	4
	Adopt standardized global certification	2

This shows that there is a number of actions that could be taken by those involved with policy and regulations to stimulate a greater uptake of bio-materials in construction. The most frequently mentioned recommendations included adopting regulations to support industrial hemp; mandates to support and fund bio-materials' acquisition of certifications, e.g. environmental product declarations; adopting the building code to allow and support bio-based innovation; developing risk matrices for building code or standard exceptions; investing in nationwide industrial composting systems; developing commercial fungi regulations and indigenous licensing models; and adopting revised genetic engineering regulations. Other recommendations included developing bio-based biosecurity import data guidelines; global efforts to regulate the term biodegradable and develop standardised global environmental certifications; taxing non-bio-materials; and developing national reuse standards and systems, e.g. regulated product stewardship.

5.2. Categories of changemaking actions

In order to highlight how certain actions vary in their ability to cause change, through direct interventions or indirect support, the participants' recommended actions have been categorised as either levers or enablers. These actions have then been sorted into five conceptual categories of actions: catalyse; certify; collaborate; create; and customize. Categories of levers of change are summarised in Table 5.5, while categories of enablers of change are summarised in Table 5.6. Although these are organised into groups to show potential more clearly, it is important to note that there are some inevitable overlaps between these.

Table 5.5: Categories of levers for change

Action	Sub-theme	Lever
Catalyse	Incentives	Mandate bio-materials for government procurement
		Mandate bio-material investment and R&D
		Provide financial kickbacks for bio-material use
		Increase carbon taxes
		Increase landfill taxes
		Tax non-bio-materials
	Standards	Adopt building code to allow bio-based innovation
Certify	Design frameworks	Contractual bio-material procurement preference
		Design frameworks adopted for bio-materials
	Regulation	Develop commercial fungi regulation
		Push indigenous fungi licensing models
		Adopt genetic engineering regulations
		Adopt regulation to support industrial hemp
		Regulate the term biodegradable
	Certification	Mandate support for bio-material certification acquisition
Collaborate	Strategic networks	Pursue collaborations with direct competitors
		Establish material research ventures
		Establish equity-for-expertise partnerships
		Partnerships between start-ups & technical consultants
		Partnerships between start-ups & larger manufacturers
		Investment partnerships with contractors & designers
Create	Circular design	Develop circular fabrication systems
		Design end-of-life decomposition
		Develop bio-based coating e.g. PLA
		Utilize prefabrication to mitigate risk
	Policy	Invest in industrial composting system
		Invest in intermediate scale infrastructure
		Invest in dedicated R&D centers

	Standards	Develop risk matrices for standard exceptions
Customise	Market strategies	Target less regulated markets first e.g. packaging or finishes
		Use radical differentiation strategy e.g. temporal qualities
	Target typologies	Target residential and interior project
		Target circular interior and retail fit-out
	Target clients	Target enthusiastic, mission-driven early adopters
		Target large portfolio clients
	Industrial symbiosis	Position bio-materials as coproduct of food system

Table 5.6: Categories of enablers for change

Action	Sub-theme	Enablers
Catalyse	Storytelling	Generate educational content for social media
		Host regular webinars (e.g. consenting, lessons learnt)
		Increase awards for dissemination
	Upskilling	Develop core bio-based tertiary programs
		Organise demos for installers
		Develop sub-contractor bio-based material training
		Practice active client education strategies
		Train early e.g. apprentice level
	Regulation	Develop bio-based import data guidelines
Certify	Storytelling	Run workshops to create consenting guidelines
	Certification	Adopt standardised global certification
	Standards	Develop reuse standards and systems
		Evolve biogenic carbon standards
Collaborate	Design frameworks	Community-driven fungal design frameworks
		Integrated design processes to de-risk
		Engage young professionals in framework development
	Ecological symbiosis	Consider wider industries' social ecosystems e.g. workers
		Understand material agency and mana
		Understand designer place in wider ecosystem
	Storytelling	Create listening environments for indigenous voices
		Prioritize multi-disciplinary holistic conversations
	Material experience	Trade shows and showcases
		Hands-on workshops with architects & contractors
		Community building workshops
	Incentives	Promote investing visa schemes
	Policy	Encourage industrial symbiosis and waste reuse
Create	Circular design	Bio-material design mindsets
	Ecological symbiosis	Practice conscious management of material production
	Industrial symbiosis	Develop digital management of stewardship and data
	Standards	Develop cycles of maintenance
Customise	Market strategies	Use conforming standardisation strategy
		Use import-based seeding strategy
	Incentives	Reflect cradle-to-cradle in costs
		Reflect planetary boundaries in costs

Tables 5.5 and 5.6 show a rich set of very specific actions which could operate as levers or enablers encouraging a greater uptake of bio-materials.

Actions that catalyse acceleration do so by transforming and educating. Direct levers for catalysing for change include incentives and standards, considered to be "push" or "pull" policies (Auerswald & Branscomb, 2003). "Push" policies for bio-materials are mandates for procurement, investment, and R&D. "Pull" policies for bio-materials incentivise risk-taking and investment in new solutions, such as carbon and landfill taxes which financially incentivise use of low-carbon circular materials. Indirect enablers for catalysing change include storytelling and upskilling disseminate knowledge which: raises awareness and understanding; inspires uptake; and trains current and future change makers (e.g. installers and architects). Enablers for raising awareness and understanding include educational content strategies (e.g. regular webinars, social media content, newsletters) targeting clients, specification and consenting stakeholders, and the general public. However, the most important step to catalyse a high uptake of bio-materials is to imbed support for it into the building code, which overlaps with certify category.

The certify category of actions is especially important for bio-materials, because certifications play a role in two different stages of the transition to bio-materials. For many other sustainable transitions, regulations are recognised as needed in the later stages of transition, once practices have already gained support, helping to formalise and normalise them (Brown et al., 2016). For bio-materials in construction, this corresponds to embedding the shift to a bioeconomy via the building code, which is noted the in the catalyse category, while other certifications are necessary for bio-materials well before reaching that stage. Building and construction are regulated through the building code and other rules and regulations, which specify the properties which building materials should have and what processes of construction should be used. Many of those regulations are not well-suited for introduction of bio-materials. Therefore, the certify category brings together the actions that can lead to certifications and setting of rules, standards, and shared accountability mechanisms to mandate and facilitate a broad scale adoption. Levers identified for certify largely focused on developing and amending regulations that are hindering early-stage innovation, and industry development of design frameworks and contractual procurement processes that require utilisation of bio-materials. There is also a need to develop, evolve and, where appropriate, reuse standards and systems to lead to greater level of certification of individual bio-materials. Enablers noted for this category are about change to standards and systems that can help certification but also included a suggestion of adopting standardised global certification, and running workshops to create consenting guidelines.

The collaborate category brings together many of the network and community creation aspects with actual collaboration through partnerships and joint ventures. As noted earlier, in order to achieve sustainable transitions, there is a need to spur both “horizontal” connections between niche actors (e.g. researchers, entrepreneurs) to foster invention, and “vertical” connections between niche actors and regime actors (e.g. business executives). This means that to stimulate a collaborative environment the system should offer many opportunities for people working in different parts of the industry to come together and know of each-other. As levers, this includes strategic networks created by pursuing collaboration with direct competitors, establishing material research ventures, and a range of other partnerships. As enablers, this includes development of design frameworks made by groups collaborators for broader groups of collaborators which can help de-risk some of the risks of the unknown (Barrier 3). It also includes trade shows, showcases and hands-on workshops, and many other dimensions such as creating listening environments for indigenous voices, understanding material agency and mana, and considering wider industry social ecosystems.

The create category of actions collated participant suggestions for a range of specific levers and enablers that need to be created to support greater uptake of bio-materials. Those include a mix of material development strategies (e.g. develop bio-based coatings), but also creating knowledge systems for circular fabrication, end-of-life, risk matrices for standard exceptions or cycles of maintenance, and setting up needed infrastructure by investing into dedicated R&D centres, digital management of stewardship and data, industrial composting systems and other needed infrastructure.

The customise category of actions were very effective in identifying a range of existing strategies which could be customised for greater support of bio-materials uptake. This included specific market strategies, such as initially targeting packaging and finishes, recommendations of suitable target typologies to effectively model opportunities, such as using interiors for case studies, but also recommendations that position bio-materials as products made from food system waste could help simulate uptake.

This analysis shows a range of categories of action that could be taken to effectively stimulate greater uptake of bio-materials in Aotearoa New Zealand.

5.3. Ambition level of change actions analysis

Developing upon the discussion on theories of change in Section 2.4, it was possible to identify three different transition stages from the initial predevelopment or seed stage, through acceleration or growth, and ultimately to thriving or stabilisation. Figure 9 was prepared by combining that with the recommended areas of influence, actors and mediums for change (Section 5.1) and categories of changemaking actions (Section 5.2). This infographic has been designed as a visual map for changemakers, across all levels and disciplines, eager to drive impactful change in the adoption of bio-materials within the construction industry.

This diagram categorises the actions identified by participants into three key dimensions:

- Leverage Points are shown on X-axis and are grouped into:
    - Levers, and
    - Enablers.
- Ambition Levels are showing on Y-axis and grouped into three ambition levels:
    - Seed – ambitions of predevelopment and foundational actions,
    - Grow – ambitions the development and early adoption phases, and
    - Thrive – ambitions of full integration of practices within industries.
- Areas of Influence are showing by the colour of text, and grouped into:
    - Scaling of innovation (orange),
    - Design and fabrication (blue),
    - Knowledge sharing (green), and
    - Policy and regulation (purple).

The infographic presents a high-level overview of the complexities involved in promoting the systemic uptake of bio-based materials in construction. It shows that different actions are most appropriate for different stages of transition, and that those actions could be levers, directly influencing a shift, or enablers, generating favourable conditions for change. It also signals the area of influence for listed actions, through which suggest potential actors, stakeholders or mediums of change. Therefore, anybody interested in taking action can review the infographic and identify a suitable action for their level of ambition, and for the particular area of influence they have.

Figure 9: Infographic summarising findings of the analysis of suggested actions and showing a range of ambition levels and possible actions for each level to drive systemic change in Aotearoa New Zealand.

Figure 9 enables focus on the needed actions, rather than specifying the exact actors or stakeholders who would be taking those actions. This is because for many needed actions, a range of actors or stakeholders could play a central role in taking action. However, if it is interpreted in terms of most obvious actors, areas of influence can be seen as aligning with particular groups the most. For example, policy and regulation actions are mostly in the domain of the government and regulatory bodies, while design and fabrication actions could be taken by material and product innovators involved with the development of the materials and their applications. While in those areas of influence the alignment with specific actors is reasonably clear, in others that might be more complex. For example, knowledge sharing actions that could be taken by interested practitioners, potential clients, but also education providers and any of those groups might take a greater lead in that area of influence. The broadest range of possible actors are needed to support scaling of innovation, because in this case the main likely actors change depending on the ambition level. This means that for the immediate actions, focused on seeding uptake, main actors would be material and product developers, but also practitioners working through applying those. For the intermediate actions, focused on growing uptake, main actors would be a combination of practitioners, builders/suppliers motivated to make a real difference in this space. While for the ambitious actions, focused on helping uptake thrive, main actors would be government and regulatory bodies.

However, Figure 9 also shows that progress in one area might rely on advancements in another. For example, seed actions (e.g., developing consenting guidelines and initial fit out pilots) can propel innovations into the development and adoption stages, enabling and justifying more comprehensive actions to take root (e.g. targeting bulk builder projects and investing in intermediate scale infrastructure). Ultimately, this visual representation aims to provide changemakers with insights into the multifaceted nature of progress in bio-based construction, showcasing how interconnected actions can collectively advance sustainability efforts within the sector. It highlights that a more immediate focus on knowledge sharing is required to enable change, as well as start-up, industry, and research bodies' investment in developing strategic partnerships to support R&D, manufacturing, and commercialisation.

6. Discussion and recommendations

This section presents insights from the research, situates those into relevant theories, and uses the discussion to form recommendations specific to Aotearoa New Zealand, although many aspects may also apply to other parts of the world.

6.1. Predevelopment to take-off transition shift

Based on the reviewed literature (Sections 1 and 2), results of the thematic analysis (Section 4) and the analysis of suggested actions (Section 5), it is possible to conclude that numerous elements indicate that in Aotearoa New Zealand, and internationally, uptake of bio-materials in construction is currently in early phases, corresponding to predevelopment stage of the sustainability transitions theories (Section 2.4.2). As the Sustainability Transition Framework explains, this is also the period when innovators and early minority are the main consumers of the innovation, according to the diffusion theory, while majority of others are in denial that the change will be needed, and there is only an emerging sense of style that reflects this phase of development (Figure 7; Section 2.4.3; Petrović, 2023). However, given the climate emergency and the triple planetary crisis, there is a real need to progress through this transition faster than the normal business-as-usual models, and a regime change requires an alignment between niche, regime and landscape to enable the acceleration. Therefore, stimulation on all levels at the same time is needed in order for this change to be achieved faster. That is why this discussion does not only examine the strategies commonly used to scale bio-materials within and immediately beyond the niche uptake, but also discusses and recommends strategies that can help mature conditions for a more intense and faster regime change.

Three aspects are critical for the preparation of general readiness for the transition on all levels. Firstly, it is important to address denial and likely anger or resistance in the broader society early on, ensuring readiness for change at the landscape level (Section 2.4.3; Petrović, 2023). Landscape pressure for change can take as diverse forms as strong and sustained top-down leadership which successfully brings along the majority in society, or a demand from the grass-roots levels. Examples of top-down leadership do not need much introduction, although these might lack sustained momentum due to political agendas changing prematurely. On the other hand, climate protests are an example of the grass-roots demand for change. Both pathways require a broad general groundswell of agreement to be achieved before the particular type of change takes place. Although the interviewees spoke about a real sense of demand for bio-materials gaining momentum, there are no indications that currently this is shared by the majority in society at large. Therefore, more work should be done to recruit and sustain a broader society support for a shift to bioeconomy in construction. This means that the general population should start learning that bio-materials are an option as the building industry learns how confidently build with those.

Secondly, unfortunately even when there is a groundswell of agreement on something (e.g. for climate action), this might not be easy to respond to if there is no clearly articulated solution (e.g. a clear way to reverse the climate change). This is because the predevelopment stage of a transition can be divided into two important steps of issue emergence and issue definition, and these stages already require a certain level of shared agreement on what the issue is (Brown et al., 2013). Only then, it is possible to start recruiting a broader support to address the issue. Therefore, the reported lack of definition of key terminology in construction around what is meant by natural, bio-based, bio-materials etc. contributes to fuzziness of the issue and effectively delaying the transition (Section 1.1). This can be resolved by developing such definitions.

Thirdly, existing research has identified that leapfrogging steps during the transition progression tends to be impossible (Brown et al., 2013; Brown et al., 2016). This is again because of the need of a broad consensus, but also because it takes time to stablish social, organisational, and economic infrastructure that is needed for the final imbedding of the new regime. For example, before cars could became the dominating transport regime, a whole lot of new systems had to be developed including not only reliable cars, but also petrol stations, car repair shops, drivers training and licencing, and so on. Such infrastructure for a greater uptake of bio-materials currently does not exist, apart from for timber. This is why timber can easily get overemphasised as the solution for a greater uptake of bio-materials, disregarding the realities, reported by the participants and others, that much timber in construction nowadays tends to come in combination with toxic chemicals either as glues or for chemical treatment (Petrović and Thomas, 2024; Marriage; 2024). Therefore, it is important to start stimulating development of the whole infrastructure needed for a greater uptake of a more diverse range of bio-materials in construction. An aspect of that is the development of professional networks, sometimes even as intermediaries, which help stimulate progression from one step within the transition to the next. (This is discussed in more detail in Section 6.2.)

The transition from niche innovation in the predevelopment stage to a greater uptake and the take-off phase can be seen as particularly risky which is why it has been recognised as “the chasm” or “Darwinian Sea” when many innovations disappear after they appear onto the market without taking-off (Sections 2.4.3 and 2.4.4). In fact, while working on this project, it became apparent that some of the novel bio-materials which succeeded to arrive on the market ended up financially collapsing not long after. A more robust process is needed, so that energy is not dissipated through the business-as-usual settings which favour incumbent actors over innovators. This is where incentives and other support could play a critical role, but those should be used in synergy with the building of a broad consensus for landscape change, using clear definitions, and stimulating development of the needed infrastructure at the same time. (This is discussed in more detail in Section 6.4.)

Based on discussions from our overseas participants, large scale top-down calls for a greater uptake of bio-materials have played a positive role in stimulating both the innovation and for the development of the other needed intermediary infrastructure. In Aotearoa New Zealand, a similar initiative was led by the Ministry of Education mandating a greater use of bio-materials in their projects. However, such government-led initiatives were reported as fragile to governmental changes, which in turn can create real setbacks. Therefore, while governmental support would be excellent, that should be combined with a more sustained support through professional organisations and similar.

Finally, despite the initial assumptions that different insights might emerge when examining views of those involved with novel bio-materials compared to more established, traditional ones, no such pattern was observed in the responses. Some stigma was still associated with even with the most established traditional materials, and they still operated in a niche – just a bit more developed niche. Therefore, these two groups are not separated in the discussion.

Recommendation 1: Establish a clear, consensus-based definition of natural, bio-based, bio-materials for use in construction.

Recommendation 2: Commit to a sustained effort to build broad public and industry support for a shift toward bio-based construction economy.

Recommendation 3: Develop and implement a multi-level strategy to accelerate and strengthen the transition to bioeconomy in construction.

Recommendation 4: Support emerging products in moving from niche innovations to mainstream adoption, while simultaneously developing the necessary infrastructure to enable wider uptake.

6.2. Knowledge and "middle-out" leadership

Responses from the participants show that there is a need for more knowledge to support the transition to a greater uptake of bio-materials in construction. More than half of the identified barriers dealt with different aspects from a lack of knowledge or misinformation (Barriers 1, 2, 3 and 5), and the development of knowledge infrastructure emerged strongly in the identified enablers (Capability Enablers 1-3, Industry Enablers 2 and 3), and in specific suggested actions (Section 5).

Other researchers have already recognised leadership of those with relevant technical knowledge as "middle-out" leadership (Janda & Parag, 2013). For the built environment, architects are typically "middle-out" leaders, although other groups with the relevant technical expertise could also play significant roles. Additionally, the Sustainability Transition Framework assumes that for different actors, the transition is likely to be faster or slower (Petrović, 2023). Appling this to the transition to greater uptake of bio-materials in construction, it suggests that some groups of actors will need to know more about bio-materials earlier than others. Therefore, one important strategy for accelerating transition to a greater uptake of bio-materials in Aotearoa New Zealand is to support development of knowledge needed for this transition.

The interview results suggest that direct experience with bio-materials is the key for a successful knowledge transfer (Capability Enablers). Therefore, hands-on experiential learning through personal experience is key, but it should be complemented and supported with the relevant scientific knowledge as much as practical. Scaling innovation area of influence (Section 5.1.1) discusses some specific suggestions from the participants which include trade shows and showcases, hands-on workshops, which also feed into community building workshops, which all contribute to the building of momentum for change but also enable peer-to-peer exchange of experiences. Knowledge sharing area of influence summarises another range of suggestions that emerged from the data set (Section 5.1.3). These suggestions include more formalised ideas such as developing tertiary programmes about bio-materials, to train students and apprentices, and creating pathways for existing industry actors to upskill. It also contains suggestions of less formal actions such development through storytelling, using a series of different forums for connecting and idea exchanging, leading to a sense of belonging and coherence within the group. Because there is a need to continue developing support and momentum for bio-materials, knowledge transfer and dissemination can also be used as to help build community to support this and to educate general population, possibly through the same events.

Although in business-as-usual models, knowledge of this nature would gradually and sequentially develop, for an acceleration of the transition, the most effective approach is to work simultaneously on all levels. Therefore, in order to accelerate uptake, it is important to develop strong strategies for development of knowledge, knowledge transfer, and a broader dissemination of knowledge about bio-materials all at the same time.

Development of knowledge is need on three key levels:

1. **Development of materials and technical solutions for their use**
   This level of knowledge development would be mainly in hands of innovators and new product developers, but also requires assistance from organisations with capabilities to test the new materials. The testing typically requires investment (the payment for the test) and that could be a suitable intervention point for the government and larger funders to support arrival of new products onto the market by simply developing a scheme that financially supports smaller bio-materials start-ups by financially supporting the needed testing.
2. **Development of guidelines for architects, specifiers and builders on using new bio-materials and systems**
   This would include typical construction details and installation guides which were recognised as needed in the Industry Enablers 2 and 3, and partly Capability Enabler 3. Suitable groups to help development of such guidelines are the special interest groups of architects and builders (such as EBANZ), but this could be supported by research and education provider organisations such as the universities, the apprentice training providers, and organisations with the interest to develop knowledge in building industry such as BRANZ.
3. **Development of a broader professional and client familiarity with bio-materials**
   This is needed to help normalise greater uptake of bio-materials in construction and responds to identified Capability Enablers, and the primary focus would be to increase general awareness about available bio-materials and through that stimulate interest. Trade shows and showcases could be an important part of this, and a broad range of individuals and groups can contribute to this development, but for a real acceleration some clarity on which group is leading the process might be useful. An existing successful example of such organisation is again EBANZ. Potentially supporting EBANZ to grow might be a solution, or development of a handful of organisations with some overlaps in focus. Alternatively, showcasing of applications might be a way of directly talking to the professionals and clients. Although actions of this nature already happen within business-as-usual, financial support for deployment of initiatives of this nature could go a long way in accelerating uptake of bio-materials in Aotearoa New Zealand.

Jointly development of knowledge on bio-materials in construction would empower “middle-out” leadership and help those ahead in the transition to effectively lead the groups that follow.

Recommendation 5: Develop professional guides and practical guidelines for using a wide range of bio-materials in construction.

Recommendation 6: Establish hands-on training programmes with bio-materials for professionals in the construction industry.

Recommendation 7: Promote bio-materials to the general public and the practitioners through activities such as tradeshows, showcases, hands-on workshops.

6.3. Supportive networks and radical collaboration

Participant suggestions often mentioned connectivity that can be achieved through the knowledge dissemination activates but also explicitly spoke about importance of supportive, interdisciplinary networks where ideas and experiences are exchanged for the benefit of all, including suggestions of collaboration with direct competitors (Section 5.2). Although one possible explanation for this is that bio-materials might be experienced by some as more a part of the needed solution for the planetary crisis rather than for short-term financial gains, and other research has also recognised networks as important for progression through the transition (Brown et al., 2013; Brown et al., 2016). This is part of the process of developing shared understanding of on the issues and solutions and also includes sociopsychological benefits of belonging to a group with similar views. Seen in this way, development of strong professional networks, can help stimulate progression from one step within the transition to the next.

Unfortunately, existing studies have revealed connectivity challenges for researchers and climate-innovators in Aotearoa New Zealand. A 2019 study presented strong views that the current Research, Science, and Innovation system "suffers from weak connectivity" between: researchers; research organisations with other research organisations; businesses with public sector research; and the local Research, Science, and Innovation system with international systems (MBIE, 2021b). Relatively low level of governmental investment in research in Aotearoa New Zealand (Section 2.4.4), and changing funding rules might be underpinning this. Networking and collaborative activities require time, and underfunding can lead to a general lack of time to research, innovate and especially to connect with others to talk about the findings. Therefore, a greater level of funding support for transition to bioeconomy in construction might be necessary in order to achieve the needed level of collaboration to support an accelerated transition.

Recommendation 8: Foster strong networks and connectivity through awareness-rising activities that promote use of bio-materials in construction. Support these efforts through research funding for bio-materials development or by stimulating their uptake in construction.

6.4. Regulative and government settings

Regulations emerged as part of top-down Industry Enabler 2, with discussion on policy and regulations as one of the important areas of influence (Section 5.1.4), and also as certify category in the discussion on types of changemaking (Section 5.2). Essentially, there was much agreement among the participants that it was possible to achieve improvements through the adjustments to the regulative settings.

A broad range of strategic and more ambitious government support initiatives have also been discussed throughout this report. On the less ambitious side of the range, strategic financial support for particularly challenging steps could prove to be very useful. As this report shows, existing regulations currently make entry of bio-materials into construction challenging, and this should be adjusted to became more supportive of the bio-materials. For example, that might be to simply financially support bio-materials start-ups with various testing of their products before those could enter the market, or to develop their LCA so they can be more competitive on the market. LCA and EPD data could play a positive role in stimulating uptake of bio-materials, but for that to be possible, data inequalities discussed in Sections 2.2, Barrier 5, and in relation to System Enabler 3, need to be addressed.

Slightly more complex regulatory adjustments are likely to be needed to accommodate participant suggestions to introduce manufacturer warranties to help de-risk unfamiliarity; creating easier paths for building permits for early applications of new materials in buildings (as an exception); and development of procurement pathways to de-risk innovation and experimentation with the new.

Finally, on the more ambitious side of the range, the government could be mandating that bio-materials have to make a more significant portion of materials used on all government funded building projects (for example, 50% of materials should be bio-based). This would stimulate development on all levels of innovation and lead to accelerated scaling of uptake.

Recommendation 9: Ensure that regulatory frameworks provide equal opportunities for the conventional and bio-based materials. Ensure LCA and EPD data for bio-materials is robust.

Recommendation 10: De-risk uptake of bio-materials in construction by creating procurement pathways which support innovation; introducing manufacturer warranties to address unfamiliarity; and by assisting start-ups with material testing.

Recommendation 11: Mandate bio-materials in government funded building projects.

6.5. Scaling niche innovation to market level

Although as noted earlier, business-as-usual pathways are unlikely to radically help accelerate transition to a greater uptake of bio-materials in construction, however, this body of knowledge does offer useful insights. The following review identifies what is needed for scaling of innovation with bio-materials in construction beyond the niche markets. These insights provide a foundation for understanding how bio-materials can transition from niche products to mainstream adoption in New Zealand's construction industry and can be used to complement other approaches discussed in this report.

6.5.1. "Fit-and-conform" vs "stretch-and-conform"

Theoretically, when new materials are introduced to market, it happens by using "fit-and-conform" or "stretch-and-conform" approaches (Smith & Raven, 2012). These two contrasting market entry strategies appear to be crucial for scaling: a conforming standardisation strategy and a radical differentiation strategy. Recommendations for the former focused on standardising bio-materials to appear as normal as possible to reduce perceived risk (in some cases even delaying introduction of more natural aesthetics until market presence was achieved), whereas recommendations for the latter focused on the opportunities for more natural and temporal products to shift perspectives on longevity and lifespans in architecture. Both are niche empowerment strategies (Smith & Raven, 2012).

Fit-and-conform is an incremental strategy aiming to renormalise bio-materials, and introduce their natural atypicality, through a slower learning curve as opposed risking the socio-cultural uncertainties of acting on a radical change to the status quo, e.g. live or highly atypical materials (Forés & Camisón, 2016). One challenge of this strategy is the sustainability disempowerment of assimilating to the status quo, such as balancing durability with ease-of-disposal or accepting introduction of synthetic components which aid fit-and-conform but increase the environmental impact of material production, upkeep, end-of-life, carbon, water-use, and land-use. Another challenge is that conforming bio-materials, by mimicking the status quo, may lose their path-breaking potential and ability to stretch-and-conform the built environment to be more circular and low-carbon (Smith & Raven, 2012). This compromised, less natural material might later become yet another incumbent regime for bio-materials to have to challenge. Finally, fit-and-conform might inhibit health and other benefits associated with natural aesthetic of bio-materials.

On the other hand, stretch-and-conform is a radical innovation approach that could provide bio-material products with first-mover advantages when applied in speed-to-market responses to windows of opportunity in the market. In this strategy, bio-materials naturalness, atypicality, and biodegradability would be used as political emblems for a built environment paradigm shift to embracing natural systems (Chen et al., 2024). For bio-materials, a stretch-and-conform approach of embracing atypical and natural aesthetics aligns with research on proving the ability of perceived naturalness to override disgust and perceived risk's influence on end-users' perception (Overvliet et al., 2016).

However, one challenge of using the stretch-and-conform strategy to stimulate uptake of bio-materials is that it is typical for more mature and established innovations (e.g. adoption of solar panels) and relies on process of change across niche, regime, and wider socio-economic landscape levels, such as socio-economic empowerment through control policies such as regulations or fiscal measures.

In the responses from the interviewees fit-and-conform strategy emerged as clear and sizable theme: Industry Enabler 1: Ease of drop-in solutions. However, this should be strategically reviewed because of the risks associated with fit-and-conform strategies and advantages of progressing with stretch-and-conform strategies. At the very least, both approaches should be developed in parallel in order to achieve a greater positive transition sooner.

Recommendation 12: Develop simultaneously drop-in solutions which work within existing rules (fit-and-conform) and radically innovative approaches how to work with bio-materials (stretch-and-conform).

6.5.2. Import-based seeding strategy and beachhead strategy

Two strategies that might be suitable for an early stage of a greater introduction of bio-materials are the import-based seeding strategy and the beachhead strategy. In Aotearoa New Zealand, import-based seeding strategy is commonly used for the introduction of novel products. This is where the introduction of new products comes via import to establish market presence and assess demand before committing to local production (Johanson & Vahlne, 1977). This is already in process, with much of hemp being imported from overseas until recently, and other exciting overseas bio-materials already on the market. Unfortunately, this is a reasonably slow process.

The beachhead strategy targets less challenging segments of the market first, in order to establish a foothold before expanding into more complex areas of the market (Moore, 2002). In order to target the less challenging segments of the market, the innovation might be initially introduced into a product category that is less regulated. For example, the introduction of bio-materials into construction packaging is likely to be less challenging than introduction into the building structure. Applications of this nature are also already on the market in Aotearoa New Zealand, or in process of arriving to the market.

Both strategies allow companies to build experience, brand recognition, assess demand and revenue streams before tackling regulation requirements of the construction industry, or investing in local production. These strategies are suitable for Aotearoa New Zealand and are already implemented for a range of bio-materials, because these are part of the business-as-usual scenario. For individual companies or bio-materials start-ups, these are a very suitable strategies, however reliance on these strategies is essentially reliance on business-as-usual. Therefore, for a more transformational transition, more radical strategies would be beneficial.

Recommendation 13: Use common niche market strategies, such as starting with imports (import-based seeding) and targeting simpler applications first (beachhead strategies), but complement them with actions that support boarder systemic transformation.

6.5.3. Bio-materials as part of food circular systems

One of the exciting recommendations from the participants was that in order to dominate the mainstream market, bio-materials should position and establish themselves as by-products and co-products of the food and beverage system. In 2024, food and beverages accounted for 30.7% of New Zealand's GDP (NZ$7,464 million), and these systems already have mature and organised waste streams e.g. hemp, straw, and wool (MBIE, 2024).

Bio-materials could be part of formalised systems which shift agricultural waste into building materials. This also reflects the market concept of becoming the whole product (Moore, 2002). For bio-materials that would mean that to deliver on the low-carbon-circular-biodegradable promise, whole product planning should be the centre of R&D investments and marketing strategies. Examples could include development of circular system integration such as, establishing local waste resource flows; circular fabrication systems; and product stewardship schemes. New Zealand has a product stewardship accreditation scheme, as part of the Waste Minimisation Act (2008), which places "responsibilities for managing end-of-life products on producers, importers, and retailers to create incentives for circular resource use" (MfE, 2024a). Focus is on ensuring proposed stewardship schemes achieve circular resource use; internalized end-of-life costs; public accountability; and collaboration. Initiatives for achieving these goals include: co-design between product groups; publicly available reports; and free and convenient collection (Sage, 2020).

Recommendation 14: Where feasible, incorporate agricultural waste into bio-materials for construction and actively promote its benefits.

6.5.4. Targeted showcases for experiential learning about bio-materials

Participant responses clearly signalled the importance of experiential learning about bio-materials, and the need for case study projects and demonstrations. However, it is important to be selective when targeting clients and typologies, since research shows that repeated positive exposure and experiences support learned acceptance of novel products (Haidt, 1997; Bliewicz et al., 2011). Participants recommended targeting residential and interior applications as they have less stringent standards, cost, and risk than structural applications and commercial projects. Interviewees explained that the reasons for this recommendation was that residential clients were personally invested in their own health and well-being, with self-build clients being even more supportive as they take more responsibility for risk. Alternatively, one participant suggested targeting clients with large portfolios who can afford innovation and, more importantly, have a responsibility to explore sustainable innovation.

Additional characteristics of early adopters for 'green' products in particular have been identified as a value for uniqueness; greater concern for the environment; interest in consuming environmentally-friendly products; less propensity for disgust; politically-liberal; younger with higher levels of education and income, and willingness to share and collaborate as industry leaders (Dunlap et al., 2000; Forté-Gardner et al., 2004; Carney et al., 2008; Inbar et al., 2009; Läpple & Rensburg, 2011; Moldovan et al., 2015; Newman & Fernandes, 2016; Powell et al., 2019; Graffi-Smith, 2021). Early adopters are considered to pay for the privilege of being a first-mover, and the associated raised social status (Kenton, 2022). It is important to consider that since often early adopters are proactively searching for ways to elevate their status and privileges – for instance, being a first-mover – and searching for solutions for challenges they face, an understanding of what pushes, or pulls, corporate demand for bio-materials will support identification of potential clients (Riverola et al., 2016).

Recommendation 15: In the early stages of the transition, target early adopters, such as younger generations who tend to be more environmentally engaged and ready to innovate.

Recommendation 16: Initially, target residential projects, retail fit-outs, and similar interior applications to showcase early use of bio-materials.

6.6. Meaning and Social Practice Theory

Interview results should also be considered through the lenses of theories from psychology and sociology introduced in Section 2.4.1. Preference for natural, bio-based materials, which were observed in Driver 1, can be seen as intrinsic motivation for a greater uptake of bio-materials in construction. Of course, many of the other factors discussed by the interviewees show that there is a complex web of influences which might shift people's actions from that direction, providing extrinsic motivations not to adopt bio-materials. However, there is a real advantage for bio-materials that they are not only preferred but also offer a range of psychophysiological benefits. Unfortunately, many other beneficial changes needed for climate action provide shallower intrinsic motivations. Therefore, psychophysiological benefits of bio-materials and preferences for those should be actively used to stimulate growth of uptake bio-materials in construction.

Similarly, the triad of key components of the Social Practice Theory, the "materials," "meanings" and "competencies," can be used to evaluate the findings from the interviews. Such analysis quickly shows that there is room for development of each of those, which might to be contributing to slower uptake at the moment. The key "materials" here are the bio-materials which are still being developed themselves, but other equally important aspects of "materials," the tools, regulations and other infrastructure needed to support uptake, which are also still being developed (with the exception of timber). Many participant responses highlighted opportunities to develop these. Similarly, the results show that "competencies" in terms of knowledge and skills needed to work and live with bio-materials also still need development. According to the Social Practice Theory, a shift in any of the three areas could lead to a change in practice and therefore continuing the existing trajectory of development the "materials" and "competencies" could lead to a positive change of practice, and of course this process could be accelerated by using a range of earlier recommendations from this report.

However, in order to accelerate the transition to a greater uptake of bio-materials in construction, "meaning" should also be used and that is where the situation is more complex. Responses show a contradictory pull between natural and bio-based materials being preferred and recognised as psychophysiological beneficial (Driver 1), while also many bio-materials are experiencing stigma (Barrier 2). This means that resolving this dynamic can present real opportunities to shift the "meaning" and support a greater uptake of bio-materials. Discussion about bio-materials as part of bioeconomy and food circular systems (Section 6.5.3) provides additional dimensions capable of shifting the "meaning" towards a greater uptake of bio-materials. Further similar synergies should be sought to strengthen the "meanings" and support a greater uptake of bio-materials, also strengthening the intrinsic motivation.

Recommendation 17: Develop and enriching the perceived value of bio-materials by linking them with other positive concepts such as the bioeconomy, circular food systems, and related sustainability themes.

7. References

AHC. (2022, July 6). *Laws & Regulations - Australian Hemp Council*. Australian Hemp Council. https://australianhempcouncil.org.au/laws-regulations/

Ajzen, I. (2012). The theory of planned behavior. In P. A. M. Lange, A. W. Kruglanski & E. T. Higgins (Eds.), *Handbook of theories of social psychology, 1*, 438-459. London, UK: Sage. https://doi.org/10.4135/9781446249215.n22

Auerswald, P. E., & Branscomb, L. M. (2003). Valleys of Death and Darwinian Seas: Financing the Invention to Innovation Transition in the United States. *The Journal of Technology Transfer*, *28*(3), 227–239. https://doi.org/10.1023/A:1024980525678

Avitabile, V., Baldoni, E., Baruth, B., Bausano, G., Boysen-Urban, K., Caldeira, C., Camia, A., Cazzaniga, N., Ceccherini, G., De Laurentiis, V., Doerner, H., Giuntoli, J., Gras, M., Guillen Garcia, J., Gurria, P., Hassegawa, M., Jasinevičius, G., Jonsson, R., Konrad, C., Kupschus, S., La Notte, A., M`barek, R., Mannini, A., Migliavacca, M., Mubareka, S., Patani, S., Pilli, R., Rebours, C., Ronchetti, G., Ronzon, T., Rougieux, P., Sala, S., Sanchez Lopez, J., Sanye Mengual, E., Sinkko, T., Sturm, V., Van Leeuwen, M., Vasilakopoulos, P., Verkerk, P.J., Virtanen, J., Winker, H. & Zulian, G., Mubareka, S., Migliavacca, M. & Sanchez Lopez, J. editors. (2023). *Biomass supply and uses in the EU.* Publications Office of the European Union, Luxembourg. DOI:10.2760/368529, JRC133505.

Barlow, C. (1991). *Tikanga whakaaro: key concepts in Māori culture.* Oxford: New Zealand Reference.

Barret, M. (2013). *Nicks head station*. Architecture AU. https://architectureau.com/articles/challenging-the-landscape-1/

BBarrett, P., & Barrett, L. (2010). The potential of positive places: Senses, brain and spaces. *Intelligent Buildings International*, *2*(3), 218–228.

Barrett, P., Davies, F., Zhang, Y., & Barrett, L. (2015). The impact of classroom design on pupils' learning: Final results of a holistic, multi-level analysis. *Building and Environment*, *89*, 118–133. https://doi.org/10.1016/j.buildenv.2015.02.013

Bellingham, P.J., Arnst, E.A., Clarkson, B.D., Etherington, T. R., Forester, L. J., Shaw, W. B., Sprague, R., Wiser, S.K., & Peltzer, D. A. (2023). The right tree in the right place? A major economic tree species poses major ecological threats. *Biological invasions, 25*(1), 39-60. https://doi.org/10.1007/s10530-022-02892-6

Blewden, E. (2024). Redefining value: supporting the uptake of low-carbon housing. Open Access Te Herenga Waka-Victoria University of Wellington. Thesis. https://doi.org/10.26686/wgtn.26087581

Bliewicz, M., Imhoff, R., & Drogosz, M. (2011). The humanity of what we eat: Conceptions of human uniqueness among vegetarians and omnivores. *European Journal of Social Psychology*, *41*(2), 201–209.

Borst, C., Congdon, A., Parker, G., & Lee, S. (2020). "Understanding "bio" material innovations: a primer for the fashion industry." *Biofabricate and Fashion for Good,* (2020). 1-20. https://www.biofabricate.co/resources.

Bošković, I., & Radivojević, A. (2023). Life cycle greenhouse gas emissions of hemp-lime concrete wall constructions in Serbia: The impact of carbon sequestration, transport, waste production and end of life biogenic carbon emission. *Journal of Building Engineering*, *66*, 105908. https://doi.org/10.1016/j.jobe.2023.105908

Bourdieu, Pierre. (1977). *Outline of a Theory of Practice.* Cambridge University Press.

Brand, S. (1997). *How buildings learn: What happens after they're built* (Rev. ed.). Phoenix Illustrated.

BRANZ. (2010). *Bulletin: Straw Bale Construction*. https://d39d3mj7qio96p.cloudfront.net/media/documents/BU530-Straw-bale-construction.pdf

Braun, V., & Clarke, V. (2006). Using thematic analysis in psychology. *Qualitative Research in Psychology*, *3*(2), 77–101. https://doi.org/10.1191/1478088706qp063oa

Braun, V., & Clarke, V. (2019). Reflecting on reflexive thematic analysis. *Qualitative Research in Sport, Exercise and Health*, *11*(4), 589–597. https://doi.org/10.1080/2159676X.2019.1628806

Braun, V., & Clarke, V. (2021). *Thematic analysis: A practical guide.* SAGE Publications, Ltd.

Brown, R., Rogers, B., & Werbeloff, L. (2016). *Moving toward water sensitive cities: a guidance manual for strategists and policy makers.* Clayton, Australia: Cooperative Research Centre for Water Sensitive Cities Pty Ltd. https://watersensitivecities.org.au/wp-content/uploads/2016/05/TMR_A4-1_MovingTowardWSC.pdf

Brown, R.R., Farrelly, M.A., & Loorbach, D.A. (2013). Actors working the institutions in sustainability transitions: the case of Melbourne's stormwater management. *Global Environmental Change, 23*(2013), 701-718. http://dx.doi.org/10.1016/j.gloenvcha.2013.02.013

Burnard, M. D., & Kutnar, A. (2015). Wood and human stress in the built indoor environment: a review. *Wood science and technology*, *49*, 969-986. DOI: 10.1007/s00226-015-0747-3

Byrne, D. (2022). A worked example of Braun and Clarke's approach to reflexive thematic analysis. *Quality & Quantity*, *56*(3), 1391–1412. https://doi.org/10.1007/s11135-021-01182-y

Carney, D. R., Jost, J. T., Gosling, S. D., & Potter, J. (2008). The secret lives of liberals and conservatives: Personality profiles, interaction styles, and the things they leave behind. *Political Psychology*, *29*(6), 807–840.

Carradine, D. (2020). Usage and uptake of engineered wood products in New Zealand. BRANZ Study Report SR453. Judgeford, New Zealand: BRANZ Ltd.

Chan, K. M. A., Boyd, D. R., Gould, R. K., Jetzkowitz, J., Liu, J., Muraca, B., Naidoo, R., Olmsted, P., Satterfield, T., Selomane, O., Singh, G. G., Sumaila, R., Ngo, H. T., Boedhihartono, A. K., Agard, J., de Aguiar, A. P. D., Armenteras, D., Balint, L., Barrington-Leigh, C., … Brondízio, E. S. (2020). Levers and leverage points for pathways to sustainability. *People and Nature*, *2*(3), 693–717. https://doi.org/10.1002/pan3.10124

Chatham House. (2020). *Policies*. Circular Economy Earth. https://circulareconomy.earth/?policy=cep

Chen, X., Xie, H., & Zhou, H. (2024). Incremental versus radical innovation and sustainable competitive advantage: a moderated mediation model. *Sustainability*, *16*, 4545. https://doi.org/10.3390/su16114545

Clarke, C., & Lockyer, O. (2022). Physical characteristics of new houses 2020. BRANZ Study Report SR465. Judgeford, New Zealand: BRANZ Ltd.

Cleantech Group. (2021). *NZ Climate Tech for the World.* (p. 209). Callaghan Innovation. https://www.callaghaninnovation.govt.nz/assets/documents/NZ_Climate_Tech_For_The_World_report.pdf

Collins, J. (2024, August 13). *New Zealand to benefit from end to gene tech ban | Beehive.govt.nz*. Beehive. https://www.beehive.govt.nz/release/new-zealand-benefit-end-gene-tech-ban

Crippa, G., Rognoli, V., & Levi, M. (2012). Materials and emotions: a study on the relations between materials and emotions in industrial products. 8th International Conference on Design and Emotion: Out of Control ,- Proceedings., 1-9.

Davis, D., Bagchi, R., & Block, L. (2015). Alliteration alters: phonetic overlap in promotional messages influences evaluations and choice. *Journal of Retailing*, *92*. https://doi.org/10.1016/j.jretai.2015.06.002

Dell, K., Houkamau, C., Mika, J., & Newth, J. (2022). Māori Perspectives on Conscious Capitalism. In *The spirit of conscious capitalism: contributions of world religions and spiritualities. Eds. Dion, M., Pava M.* (pp. 379-397). Springer International Publishing. https://doi.org/10.1007/978-3-031-10204-2_20

Dhakal K. (2022). NVivo. *Journal of the Medical Library Association*, *110*(2), 270–272. https://doi.org/10.5195/jmla.2022.1271

Doran, G. T. (1981). There's a S.M.A.R.T. way to write management's goals and objectives. *Management Review*, *70*(11), 35.

Dunlap, R. E., Van Liere, K. D., Mertig, A. G., & Jones, R. E. (2000). New trends in measuring environmental attitudes: Measuring endorsement of the new ecological paradigm: a revised NEP scale. *Journal of Social Issues*, *56*(3), 425–442.

Dunningham, E.A., Steward, G.A., (Gregory A., Quinlan, P., Firm, D., Gaunt, D., Riley, S., Lee, J., Dunningham, A. G. (Andrew G.), & Radford, R. (2020). Tōtara industry pilot project: final summary report (V.2.1, August 2020). Tane's Tree Trust.

EBANZ. (2024). *Earth Building Standards – Earth Building Association of New Zealand*. https://www.earthbuilding.org.nz/earth-building-standards/

EBOSS. (2021). Construction supply chain report. Available from: https://www.eboss.co.nz/insights/construction-supply-chain-report/q3-2021/background

Ecovative Design. (2023, December 13). About: Our Story. Ecovative Design. The Mycelium Technology Company. https://www.ecovative.com/pages/our-story#

Egan, C., Cristino, F., Payne, J. S., Thierry, G., & Jones, M. W. (2020). How alliteration enhances conceptual-attentional interactions in reading. *Cortex; a Journal Devoted to the Study of the Nervous System and Behavior*, *124*, 111–118. https://doi.org/10.1016/j.cortex.2019.11.005

EU. (2023). *Regulation of the European Parliament and of the Council on plants obtained by certain new genomic techniques and their food and feed, and amending Regulation (EU) 2017/625* (p. 70). European Commission. https://food.ec.europa.eu/document/download/c03805a6-4dcc-42ce-959c-e4d609010fa3_en?filename=gmo_biotech_ngt_proposal_2023-411_en.pdf

EU. (2024, September 1). *Bioeconomy Strategy | Knowledge for policy*. Knowledge For Policy. https://knowledge4policy.ec.europa.eu/bioeconomy/bioeconomy-strategy_en#ep_natstrat

European Commission. (2024). *Revised Energy Performance of Buildings Directive (EPBD)*. https://ec.europa.eu/commission/presscorner/detail/en/qanda_24_1966

Evison, D.C., Kremer, P.D., & Guiver, J. (2018). Mass timber construction in Australia and New Zealand – status, and economic and environmental influences on adoption. *Wood and Fibre Science*, 128–138. https://wfs.swst.org/index.php/wfs/article/view/2713

Ewers, R. M., Kliskey, A. D., Walker, S., Rutledge, D., Harding, J. S., & Didham, R. K. (2006). Past and future trajectories of forest loss in New Zealand. *Biological conservation, 133*(3), 312-325. https://doi.org/10.1016/j.biocon.2006.06.018

Florentin, Y., Pearlmutter, D., Givoni, B., & Gal, E. (2017). A life-cycle energy and carbon analysis of hemp-lime bio-composite building materials. *Energy and Buildings*, *156*, 293–305. https://doi.org/10.1016/j.enbuild.2017.09.097

Forés, B., & Camisón, C. (2016). Does incremental and radical innovation performance depend on different types of knowledge accumulation capabilities and organizational size? *Journal of Business Research*, *69*(2), 831–848. https://doi.org/10.1016/j.jbusres.2015.07.006

Forté-Gardner, O., Young, F. L., Dillman, D. A., & Carroll, M. S. (2004). Increasing the effectiveness of technology transfer for conservation cropping systems through research and field design. *Renewable Agriculture and Food Systems*, *19*(4), 199–209. https://doi.org/10.1079/RAFS200485

Frumkin, H., Bratman, G. N., Breslow, S. J., Cochran, B., Kahn Jr, P. H., Lawler, J. J., ... & Wood, S. A. (2017). Nature contact and human health: A research agenda. *Environmental health perspectives*, *125*(7), 075001. DOI: https://doi.org/10.1289/EHP1663

García-Salazar, J. A., Skaggs, R. K., & Crawford, T. L. (2012). World price, exchange rate and inventory impacts on the Mexican corn sector: A case study of market volatility and vulnerability. *Interciencia*, *37*(7), 498-505.

Garner, G. O. (2017). Forestry treaty claims in Aotearoa-New Zealand: bicultural significance and socio-economic impact. *Pacific Rim Property Research Journal, 23*(1), 35–49. https://doi.org/10.1080/14445921.2017.1299442

Geels, F. W. (2002). Technological transitions as evolutionary reconfiguration processes: a multi-level perspective and a case-study. *Research Policy*, *31*(8), 1257–1274. https://doi.org/10.1016/S0048-7333(02)00062-8

Geels, F. W. (2004). From sectoral systems of innovation to socio-technical systems: insights about dynamics and change from sociology and institutional theory. *Research Policy*, *33*, 897–920. https://doi.org/10.1016/j.respol.2004.01.015

Geels, F. W. (2011). The multi-level perspective on sustainability transitions: responses to seven criticisms. *Environmental Innovation and Societal Transitions*, *1*(1), 24–40. https://doi.org/10.1016/j.eist.2011.02.002

Geels, F. W. (2018). Socio-technical transitions to sustainability. In F. W. Geels, *Oxford Research Encyclopedia of Environmental Science*. Oxford University Press. https://doi.org/10.1093/acrefore/9780199389414.013.587

Geels, F. W., & Schot, J. (2007). Typology of sociotechnical transition pathways. *Research Policy*, *36*(3), 399–417. https://doi.org/10.1016/j.respol.2007.01.003

Geels, F. W., Berkhout, F., & van Vuuren, D. P. (2016). Bridging analytical approaches for low-carbon transitions. *Nature Climate Change*, *6*(6), 576–583. https://doi.org/10.1038/nclimate2980

Genus, A., & Coles, A.-M. (2008). Rethinking the multi-level perspective of technological transitions. *Research Policy*, *37*(9), 1436–1445. https://doi.org/10.1016/j.respol.2008.05.006

Gilbert, J. A., & Hartmann, E. M. (2024). The indoors microbiome and human health. *Nature Reviews Microbiology*, 1-14.

Gladwell, V., Brown, D., Barton, J., Tarvainen, M., Kuoppa, P., & Pretty, J. (2012). The effects of views of nature on autonomic control. *European Journal of Applied Physiology*, *112*, 3379–3389.

Glanz, K. (2005). *Theory at a glance: A guide for health promotion practice* (2nd ed.). United States National Cancer Institute. http://www.sbccimplementationkits.org/demandrmnch/wp-content/uploads/2014/02/Theory-at-a-Glance-A-Guide-For-Health-Promotion-Practice.pdf

Graffi-Smith, D. (2021). A call for accountability and action. *Deloitte Global MillenialMillennial Survey*, 39. https://www.deloitte.com/za/en/about/people/social-responsibility/millennialsurvey-2021.html

Green, M. (2022). *Alliteration and assonance as mnemonic devices in second language word-pair learning* [Cardiff University]. https://orca.cardiff.ac.uk/id/eprint/159783/1/MikeGreen_PhD_Thesis%20FINAL.pdf

Griffiths, A. (2021, July 29). *Barrault Pressacco uses hempcrete to create social housing in Paris*. Dezeen. https://www.dezeen.com/2021/07/29/barrault-pressacco-biomaterials-social-housing-paris/

Haidt, J. (1997). Body, psyche, and culture: the relationship between disgust and morality. *Psychology and Developing Societies*, *9*, 107–131.

Hamzaoui Essoussi, L., & Linton, J. D. (2010). New or recycled products: How much are consumers willing to pay? *Journal of Consumer Marketing*, *27*(5), 458–468. https://doi.org/https://doi.org/10.1108/07363761011063358 .

Han, K. (2010). An exploration of relationships among the responses to natural scenes: scenic beauty, preference, and restoration. *Environment and Behavior*, *42*, 243–270.

Hartig, T., Mitchell, R., De Vries, S., & Frumkin, H. (2014). Nature and health. *Annual review of public health, 35*(1), 207-228. DOI: https://doi.org/10.1146/annurev-publhealth-032013-182443

Holcim Foundation. (2014). Reinventing the brick: Zero carbon emissions compostable structure, New York, USA. *Holcim Awards Bronze 2014 North America,* p.61-64. https://www.holcimfoundation.org/article/reinventing-the-brick

Hudecki, A., Kiryczynski, G., & Łos, M.J. (2019). Biomaterial, definition, overview. *Stem Cells and Biomaterials for Regenerative Medicine*. Eds. Łos, M.J., Hudecki, A., Wiecherć, E. Academic Press. https://doi.org/10.1016/B978-0-12-812258-7.00007-1

Inbar, Y., Pizarro, D. A., & Bloom, P. (2009). Conservatives are more easily disgusted than liberals. *Cognition and Emotion*, *23*(4), 714–725.

IPCC. (2023). *Climate Change 2023: Synthesis Report. Contribution of Working Groups I, II and III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [Core Writing Team, H. Lee and J. Romero (eds.)]. IPCC, Geneva, Switzerland.* (First). Intergovernmental Panel on Climate Change (IPCC). https://doi.org/10.59327/IPCC/AR6-9789291691647

Jamieson, A. (2023, September 14). *The Circular Economy: What does it mean for Aotearoa New Zealand's construction sector and what are the opportunities?* https://www.pwc.co.nz/services/sustainability-climate-and-nature/the-circular-economy-what-does-it-mean-for-aotearoa-new-zealand.html

Janda, K.B., & Parag, Y. (2013). A middle-out approach for improving energy performance in buildings. *Building Research & Information*, *41*(1), 39-50.

Jo, C., Zhang, J., Tam, J. M., Church, G. M., Khalil, A. S., Segrè, D., & Tang, T.-C. (2023). Unlocking the magic in mycelium: Using synthetic biology to optimize filamentous fungi for biomanufacturing and sustainability. *Materials Today Bio*, *19*, 100560. https://doi.org/10.1016/j.mtbio.2023.100560

Johanson, J., & Vahlne, J.-E. (1977). The internationalization process of the firm: a model of knowledge development and increasing foreign market commitments. *Journal of International Business Studies*, *8*(1), 23–32.

Karana, E., & Nijkamp, N. (2014). Fiberness, reflectiveness and roughness in the characterization of natural and high quality materials. *Journal of Cleaner Production*, *68*, 252–260. https://doi.org/10.1016/j.jclepro.2014.01.001

Keelan, T.J. (2014). *Nga reanga youth development Māori styles.* ePress Unitec, Auckland.

Kemp, R. (1994). Technology and the transition to environmental sustainability: the problem of technological regime shifts. *Futures* 26(10): 1023-1046.

Kemp, R.,, & Rotmans, J. (2005). The Management of the Co-Evolution of Technical, Environmental and Social Systems. In M. Weber & J. Hemmelskamp (Eds.), *Towards Environmental Innovation Systems* (pp. 33–55). Springer. https://doi.org/10.1007/3-540-27298-4_3

Kemp, R., Schot, J., & Hoogma, R. (1998). Regime shifts to sustainability through processes of niche formation: The approach of strategic niche management. *Technology Analysis & Strategic Management*, *10*(2), 175–198. https://doi.org/10.1080/09537329808524310

Kenton, W. (2022, December 27). *What Is an Early Adopter, and How Does It Work (With Examples)?* Investopedia. https://www.investopedia.com/terms/e/early-adopter.asp

Läpple, D., & Rensburg, T. V. (2011). Adoption of organic farming: Are there differences between early and late adoption? *Ecological Economics*, *70*(7), 1406–1414. https://doi.org/10.1016/j.ecolecon.2011.03.002

Li, X., Zhang, Z., Gu, M., Jiang, D., & Wang, J. (2012). Effects of plantscape colors on psycho-physiological responses of university students. *Journal of Food, Agriculture & Environment*, *10*, 702–708.

Madusanka, C., Udayanga, D., Nilmini, R., Rajapaksha, S., Hewawasam, C., Manamgoda, D., & Vasco-Correa, J. (2024). A review of recent advances in fungal mycelium based composites. *Discover Materials*, *4*(1), 13. https://doi.org/10.1007/s43939-024-00084-8

Magwood, C. (2016). *Essential Hempcrete Construction: The Complete Step-by-Step Guide*. New Society Publishers. http://ebookcentral.proquest.com/lib/vuw/detail.action?docID=4547884

Markard, J., Raven, R., Truffer, B., (2012). Sustainability transitions: an emerging field of research and its prospects. *Research Policy, 41*(2012); 955-967. DOI: 10.1016/j.respol.2012.02.013.

Marriage, G. (2024). Timber: industrial process, treatments and adhesives. In *Sustainability and Toxicity of Building Materials: manufacture, use and disposal stages.* Eds. Petrović, E.K., Gjerde, M., Chicca, F., & Marriage, G. Cambridge, MA; London, UK: Woodhead Publishing, 149-178.

Marsden, M.O., & Royal, T.A.C. (2003). *The woven universe: selected writings of Rev. Māori Marsden*. Estate of Rev. Māori Marsden.

Mayol, E. (2012). Growing Architecture through Mycelium and Agricultural Waste. *The International Journal of the Constructed Environment, 1*(4), 87-90. http://constructedenvironment.com/journal/

MBIE. (2021a). *Construction sector trends: biannual snapshot: November 2021*. Ministry of Business, Innovation & Employment. https://www.mbie.govt.nz/assets/construction-sector-trends-biannual-snapshot-november-2021.pdf

MBIE. (2021b). *Te Ara Paerangi Future Pathways Green Paper 2021* (p. 43). Ministry of Business Innovation & Employment. https://www.mbie.govt.nz/have-your-say/future-pathways

MBIE. (2024, July 29). *Circular Economy and Bioeconomy | Ministry of Business, Innovation & Employment*. https://www.mbie.govt.nz/business-and-employment/economic-development/circular-economy-and-bioeconomy

MBIE. (2024, July 29). *Circular Economy and Bioeconomy | Ministry of Business, Innovation & Employment*. https://www.mbie.govt.nz/business-and-employment/economic-development/circular-economy-and-bioeconomy

Meelen, T., & Farla, J. (2013). Towards an integrated framework for analysing sustainable innovation policy. *Technology Analysis & Strategic Management*, *25*(8), 957–970. https://doi.org/10.1080/09537325.2013.823146

MfE. (2023, January 18). *Mandatory climate-related disclosures*. Ministry for the Environment. https://environment.govt.nz/what-government-is-doing/areas-of-work/climate-change/mandatory-climate-related-financial-disclosures/

MfE. (2024a, April 3). *Product stewardship accreditation*. Ministry for the Environment. https://environment.govt.nz/what-government-is-doing/areas-of-work/waste/product-stewardship/product-stewardship-accreditation/

MfE. (2024b, June 4). *Overview of the waste disposal levy*. Ministry for the Environment. https://environment.govt.nz/what-government-is-doing/areas-of-work/waste/waste-disposal-levy/overview/

Mfon, I. (2023). Aesthetic considerations in architectural design: exploring pleasure, arousal, and dominance. *International Journal of Research Publication and Reviews*, *4*(8), 923-935.

Miller, R., Dickinson, Y., & Reid, A. (2007). Māori connections to forestry in New Zealand. *Forestry for Indigenous Peoples, 13*.

MoE. (2018, August 24). *Understanding pedagogy as integral to innovative learning environments*. Inclusive Education. https://inclusive.tki.org.nz/guides/planning-innovative-learning-environments-iles/understanding-innovative-learning-environments/

Moldovan, S., Steinhart, Y., & Ofen, S. (2015). "Share and scare": solving the communication dilemma of early adopters with a high need for uniqueness. *Journal of Consumer Psychology*, *25*(1), 1–14. https://doi.org/10.1016/j.jcps.2014.06.001

Moore, G. A. (2002). *Crossing the chasm: marketing and selling disruptive products to mainstream customers* (Rev. ed.). Harper Business Essentials.

Morgan, E.d R., Nigel B. Perry N.B., & David Chagné D. (2019). Science at the intersection of cultures – Māori, Pākehā and mānuka, *New Zealand Journal of Crop and Horticultural Science, 47*(:4), 225-232., DOI: 10.1080/01140671.2019.1691610

MPI. (2020, November 16). *Introduction to biosecurity legislation | NZ Government*. Ministry for Primary Industries. https://www.mpi.govt.nz/legal/legislation-standards-and-reviews/biosecurity-legislation/introduction-to-biosecurity-legislation/

MTEH. (2024, June 10). *RE2020 Environmental Regulation | Ministry of Partnership with Territories and Decentralisation Ministry of Ecological Transition, Energy, Climate and Risk Prevention Ministry of Housing and Urban Renewal*. https://www.ecologie.gouv.fr/politiques-publiques/reglementation-environnementale-re2020

Murray, M. (2024). Beyond the hemp house: exploring potential for the deployment of hempcrete in Aotearoa's medium-density housing. Open Access Te Herenga Waka-Victoria University of Wellington. Thesis. https://doi.org/10.26686/wgtn.25763931

Murray, M., & Petrović, E.K. (2023). Hempcrete housing: a preliminary evaluation of the relationship between housing typology and demand on agricultural land. In Proceedings of the 56th International Conference of the Architectural Science Association: Sustainability and health: the nexus of carbon-neutral architecture and well-being. Eds. M. Dewsbury, D. Tanton, pp. 330-343. DOI: https://doi.org/10.25455/wgtn.26401966

Newman, T. P., & Fernandes, R. (2016). A re-assessment of factors associated with environmental concern and behavior using the 2010 General Social Survey. *Environmental Education Research*, *22*(2), 153–175.

Ngāti Hine Leads Development of World First Indigenous Forestry Strategy. (2022). Te Ahuahu. Retrieved 20/05 from https://teahuahu.nz/2022/06/22/ngati-hine-leads-development-of-world-first-indigenous-forestry-strategy/

Nguyen, L., Bayne, K., & Altaner, C. (2021). A review of kōwhai (Sophora spp.) and its potential for commercial forestry. *New Zealand journal of forestry science*, *51*(8). https://doi.org/10.33494/nzjfs512021x157x

NZHIA. (2024, October 2). The NZHIA 2024 Media Campaign: iHemp is NOT a drug! *New Zealand Hemp Industries Association*. https://nzhia.com/association-news/the-nzhia-2024-media-campaign-ihemp-is-not-a-drug/

Overvliet, K. E., Karana, E., & Soto-Faraco, S. (2016). Perception of naturalness in textiles. *Materials & Design*, *90*, 1192–1199. https://doi.org/10.1016/j.matdes.2015.05.039

Parag, Y., & Janda, K.B. (2014). More than filler: Middle actors and socio-technical change in the energy system from the "middle-out". *Energy Research & Social Science*, *3*, 102-112.

Parfitt, R. L., & Ross, D. J. (2011). Long-term effects of afforestation with Pinus radiata on soil carbon, nitrogen, and ph: a case study. Soil research (Collingwood, Vic.), 49(6), 494. https://doi.org/10.1071/SR111061838-675X/11/060494

Peters, C. J., Picardy, J., Darrouzet-Nardi, A. F., Wilkins, J. L., Griffin, T. S., & Fick, G. W. (2016). Carrying capacity of US agricultural land: Ten diet scenarios. *Elementa*, *4*, 000116. https://doi.org/10.12952/journal.elementa.000116

Petrović, E. (2014). Building materials and health: a study of perceptions of the healthiness of building and furnishing materials in homes. Open Access Te Herenga Waka-Victoria University of Wellington. Thesis. https://doi.org/10.26686/wgtn.17006302.v1

Petrović, E.K. (2017). An overview of health hazards from materials: application of principles. In *Materials for a healthy, ecological and sustainable built environment: principles for evaluation.* Eds. Petrović, E.K., Vale, B., Pedersen Zari, M. Duxford, UK: Woodhead Publishing, 203-236.

Petrović, E.K. (2023). Sustainability Transition Framework: an integrated conceptualisation of sustainability change. *Sustainability*, *16*, 217. https://doi.org/10.3390/su16010217

Petrović, E.K., & Thomas, C.A. (2024). Sustainability and toxicity of formaldehyde-based resins for composite wood products like plywood, particleboard and medium density fibreboard. In *Sustainability and Toxicity of Building Materials: manufacture, use and disposal stages.* Eds. Petrović, E.K., Gjerde, M., Chicca, F., & Marriage, G. Cambridge, MA; London, UK: Woodhead Publishing, 389-415.

Petrović, E.K., Vale, B., Wilson, M.S. (2016). Vinyl and linoleum flooring: health issues as perceived by lay people and architects. *Journal of Green Building, 11*(1): 159-177. https://doi.org/10.3992/jgb.11.1.159.1

Porter, M. E. (1991). Towards a dynamic theory of strategy. *Strategic Management Journal*, *12*, 95–117. https://www.jstor.org/stable/2486436

Powell, P. A., Jones, C. R., & Consedine, N. S. (2019). It's not queasy being green: the role of disgust in willingness-to-pay for more sustainable product alternatives. *Food Quality and Preference*, *78*, 103737. https://doi.org/10.1016/j.foodqual.2019.103737

Quinn, J. (2022). *High Performance Construction Details Handbook*. https://passivehouse.nz/wp-content/uploads/2022/04/PHINZ_HPCD_Handbook_220419_highres.pdf

Raanaas, R., Evensen, K., Rich, D., Sjostrom, G., & Patil, G. (2011). Benefits of indoor plants on attention capacity in an office setting. *Journal of Environmental Psychology*, *31*, 99–105.

Radivojević, A., Roter-Blagojević, M., & Djukanović, Lj. (2017). Sustainability and the material aspect of traditional residential buildings in Serbia. In *Materials for a healthy, ecological and sustainable built environment: principles for evaluation.* Eds. Petrović, E.K., Vale, B., Pedersen Zari, M. Duxford, UK: Woodhead Publishing, 239-254.

Ripple, W. J., Wolf, C., Gregg, J. W., Rockström, J., Mann, M. E., Oreskes, N., Lenton, T. M., Rahmstorf, S., Newsome, T. M., Xu, C., Svenning, J.-C., Pereira, C. C., Law, B. E., & Crowther, T. W. (2024). The 2024 state of the climate report: Perilous times on planet Earth. *BioScience*, *74*(12), 812-824. https://doi.org/10.1093/biosci/biae087

Riverola, C., Dedehayir, O., & Miralles, F. (2016). Who are the early adopters in the diffusion of innovations? A literature review. In *ANZAM Conference (Australian & New Zealand Academy of Management)*.

Roberts, M., Norman, W., Minhinnick, N., Wihongi, D., & Kirkwood, C. (1995). Kaitiakitanga: Māori perspectives on conservation. Pacific Conservation Biology, 2(1), 7–7. https://doi.org/10.1071/PC950007

Runge, C.F., & Senauer, B.S. (2007). How biofuels could starve the poor. *The New York Times*. https://archive.nytimes.com/www.nytimes.com/cfr/world/20070501faessay_v86n3_runge_senauer.html?_r=0&pagewanted=print

Ryan, R. M., & Deci, E. L. (2000). Intrinsic and extrinsic motivations: classic definitions and new directions. *Contemporary educational psychology*, *25*(1), 54-67.

Sage, E. (2020, July 29). *General guidelines for product stewardship schemes for priority products notice 2020—2020-go3342- New Zealand Gazette*. Gazette. https://gazette.govt.nz/notice/id/2020-go3342

Shah, N. (2024). Exploring the psycho-physiological benefits of biomaterials in architecture: a seaweed case study investigating making and human response. Open Access Te Herenga Waka-Victoria University of Wellington. Thesis. https://doi.org/10.26686/wgtn.26377963

Shove, E. (2012). *Connecting practices: large topics in society and social theory.* London: Routledge. https://doi.org/10.4324/9781003275107

Smale, A. (2024). *Tairāwhiti: Pine, Profit and the Cyclone* (H. Bennett, Ed.). Bridget Williams Books.

Smith, A., & Raven, R. (2012). What is protective space? Reconsidering niches in transitions to sustainability. *Research Policy*, *41*(6), 1025–1036. https://doi.org/10.1016/j.respol.2011.12.012

Standards New Zealand. (2024). *NZS 4298:2024 Materials and construction for earth buildings*. https://www-standards-govt-nz.eu1.proxy.openathens.net/shop/NZS-42982024

Standards New Zealand. (2024). *NZS 4298:2024 Materials and construction for earth buildings*. https://www-standards-govt-nz.eu1.proxy.openathens.net/shop/NZS-42982024

Subasinghe, Y. (2024). Green grows houses: explorations into reducing built environment embodied carbon emissions by promoting strawbale as a construction material. Open Access Te Herenga Waka-Victoria University of Wellington. Thesis. https://doi.org/10.26686/wgtn.27129846

Sun, H., Teh, P.-L., & Linton, J.D. (2018). Impact of environmental knowledge and product quality on student attitude toward products with recycled/remanufactured content: implications for environmental education and green manufacturing. *Business Strategy and the Environment*, *27*(7), 935–945. https://doi.org/10.1002/bse.2043

Sustainable Engineering Ltd. (2024, December 20). Hiberna Strawbale House. *Sustainable Engineering Ltd.* https://sustainableengineering.co.nz/casestudy/hiberna-strawbale-house/

Taylor, L. (2024, June 24). *Australia sets ambitious targets for environmental conservation and circular economy development*. http://acehub.org.au/news/australia-sets-ambitious-targets-for-environmental-conservation-and-circular

Tran Le, A.D., Maalouf, C., Mai, T.H., Wurtz, E., & Collet, F. (2010). Transient hygrothermal behaviour of a hemp concrete building envelope. *Energy and Buildings*, *42*(10), 1797–1806. https://doi.org/10.1016/j.enbuild.2010.05.016

Tsunetsugu, Y., Miyazaki, Y., & Sato, H. (2007). Physiological effects in humans induced by the visual stimulation of room interiors with different wood quantities. *Journal of Wood Science*, *53*, 11-16. DOI: 10.1007/s10086-006-0812-5

UNEP, United Nations Environment Programme (2024): *Global resources outlook 2024: bend the trend – pathways to a liveable planet as resource use spikes.* International Resource Panel. Nairobi. Available from: https://wedocs.unep.org/20.500.11822/44901

UNEP, United Nations Environment Programme. (2023a). *Building materials and the climate: constructing a new future*. United Nations Environment Programme. Nairobi. https://wedocs.unep.org/xmlui/handle/20.500.11822/43293

UNEP, United Nations Environment Programme. (2023b). *Broken record temperatures hit new highs, yet world fails to cut emissions (again)*. https://doi.org/10.1163/9789004322714_cclc_2023-0252-1155

USDA. (2024, November 11). *FACT SHEET: Overview of USDA's BioPreferred Program | USDA*. USDA. https://www.usda.gov/media/press-releases/2016/02/18/fact-sheet-overview-usdas-biopreferred-program

Venture Taranaki. (2022). *Branching out blueprint: Hemp fibre for construction*. https://www.venture.org.nz/assets/Uploads/Hemp-Blueprint-Final-v2.pdf

Vincent, E., Battisto, D., & Grimes, L. (2010). The effects of presence and influence in nature images in a simulated hospital patient room. *Herd*, *3*, 56–69.

Waitangi Tribunal., (2011). Ko Aotearoa tēnei a report into claims concerning New Zealand law and policy affecting Māori culture and identity (report No. Wai 262). Legislation Direct. https://forms.justice.govt.nz/search/Documents/WT/wt_DOC_68356054/KoAotearoaTeneiTT1W.pdf

Walker, M. (2022). *A mycelium connection: a study of the influence of mycelium bio-composites' senso-aesthetics on disgust, and other barriers to uptake in architecture* [Thesis, Open Access Te Herenga Waka-Victoria University of Wellington]. https://doi.org/10.26686/wgtn.20621103

Walker, R., & Morris, H. (2021). *Development of the New Zealand Earth Building Standards NZS 4297:2020, NZS 4298:2020 and NZS4299:2020*. SESOC Conference, Hamilton, New Zealand. https://2021conf.sesoc.org.nz/PDFs/S4B%20P3%20-%20Walker_Morris.pdf

Wannan, O. (2022). Why the pine tree might land the Government in court. *Stuff*. https://www.stuff.co.nz/environment/climate-news/128741070/why-the-pine-tree-might-landthe-government-in-court

Warbrick, I., Makiha, R., Heke, D., Hikuroa, D., Awatere, S., & Smith, V. (2023). Te Maramataka—an indigenous system of attuning with the environment, and its role in modern health and well-being.

International journal of environmental research and public health, *20*(3), 2739. https://doi.org/10.3390/ijerph20032739

Winter, C.J. (2020). Does time colonise intergenerational environmental justice theory? *Environmental politics*, *29*(2), 278-296. https://doi.org/10.1080/09644016.2019.1569745

World Bank. (2025a, May 1). Research and development expenditure (% of GDP) – OECD members. https://data.worldbank.org/indicator/GB.XPD.RSDV.GD.ZS?locations=OE&most_recent_value_desc=false

World Bank. (2025b, May 1). GDP (current US$) – OECD members. https://data.worldbank.org/indicator/NY.GDP.MKTP.CD?locations=OE&most_recent_value_desc=true

Yates, A.M. (2021). Transforming geographies: Performing Indigenous-Māori ontologies and ethics of more-than-human care in an era of ecological emergency. *New Zealand geographer*, *77*(2), 101-113. https://doi.org/10.1111/nzg.12302