How Sustainable Materials Are Judged in Motion: Designing and Testing a Hybrid Carbon–Flax Composite Gravel Bicycle Frame

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Fig. 1. 3T Extrema Italia Model that was re-engineered.

High-performance bicycle frames are predominantly manufactured from carbon-fibre composites due to their favourable stiffness-to-weight ratio. However, carbon fibre production is energy-intensive, petroleum-based and difficult to recycle, raising concerns about long-term sustainability. Although vegetal and mineral fibres offer environmental benefits, their adoption in performance-oriented bicycle frames remains limited due to concerns about structural performance and user acceptance. This paper presents a design-through-making study exploring the integration of sustainable composite materials, specifically flax, hemp and basalt fibres, into a full-scale, rideable gravel bicycle frame. A hybrid composite frame was produced using filament winding and resin transfer moulding, selectively incorporating vegetal fibres while remaining compatible with industrial production constraints. Finite element simulations guided material selection, and physical stiffness testing verified structural performance against industry benchmarks. A mixed-method study with 13 experienced riders showed that judgement depended less on stiffness and more on material visibility, perceived sustainability, and trust, indicating potential for sustainable composites in performance bicycle design.

Additional Key Words and Phrases: Sustainable composites, Bicycle frame design, Natural fibre, Filament winding, Rider perception, Flax, Basalt, Hemp

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Vegetal fibres

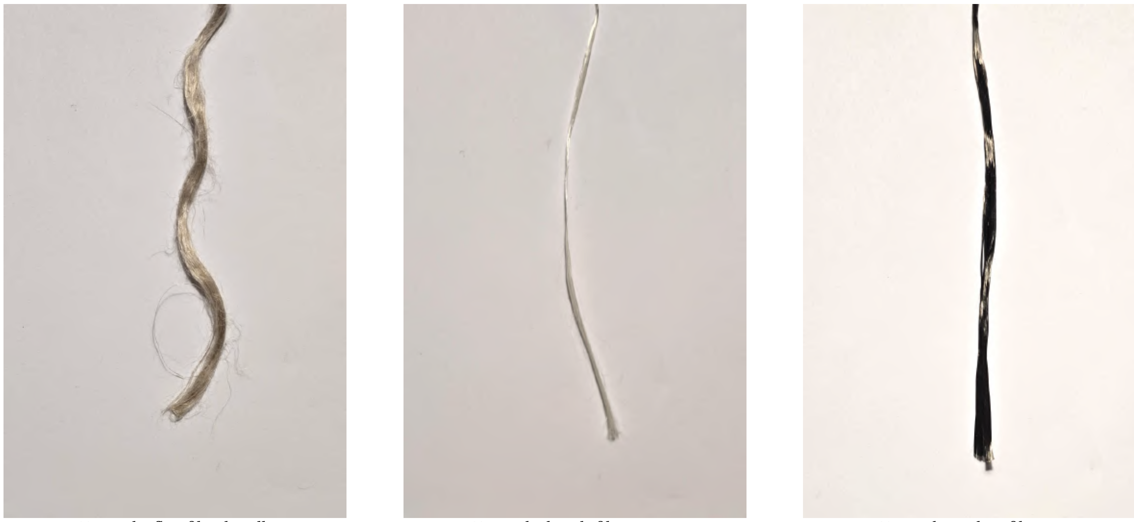
Derived from plants (e.g. hemp or flax); renewable and biodegradable [13].

Mineral fibres

Produced from minerals (e.g (basalt); high thermal stability and strength [11, 17].

Synthetic fibres

Man-made (e.g. carbon or glass); typically reliant on non-renewable fossil resources [13].



Example: flax fibre bundle *Example: basalt fibre roving* *Example: carbon fibre tow*

Fig. 2. Fibre types used in this work, with representative photographic samples.

1 INTRODUCTION

The transportation sector is currently responsible for approximately 23% of global CO_2 emissions [20]. Although emission reduction efforts have historically focused on vehicle operation, emissions associated with manufacturing processes and global logistics remain substantial. In this context, bicycles represent a low-emission alternative for everyday mobility—particularly for short and last-mile trips—while also providing significant health benefits [27, 28]. Consequently, cycling is increasingly recognised as a key component of sustainable urban transport strategies [4, 7].

However, sustainability in mobility cannot be evaluated solely through operational efficiency. Material selection and manufacturing processes play a critical role in determining the environmental impact, industrial feasibility, and how artefacts are experienced in use. Therefore, this study examines how material and manufacturing choices shape the embodied experience, perception, and trust of cyclists during real-world riding, treating sustainability not as an abstract performance metric but as something that becomes meaningful through lived interaction. This perspective directly motivates an investigation into both industrial integration and user experience, which form the basis of the research questions addressed in this work.

The bicycle market has evolved to address a wide range of mobility and performance demands, including city, mountain, and road bicycles. More recently, gravel bicycles (hybrid models that combine the characteristics of road and mountain bicycles) have gained popularity due to their versatility in mixed terrains, making them suitable for commuter and recreational use [22, 23]. Despite this growth, gravel cycling remains a niche segment within the broader bicycle market, predominantly adopted by experienced cyclists and early adopters of new technologies and materials. From a research perspective, gravel bicycles provide a representative platform for material and manufacturing experimentation, as they must balance structural robustness, comfort, durability, and visual identity across varied riding conditions. This makes them particularly suitable for studying how alternative composite materials can be integrated into rideable, performance-relevant frames. Against this backdrop, increasing attention has been directed towards alternative composite materials that reduce reliance on petroleum-based carbon fibres. In composite bicycle frame manufacturing,

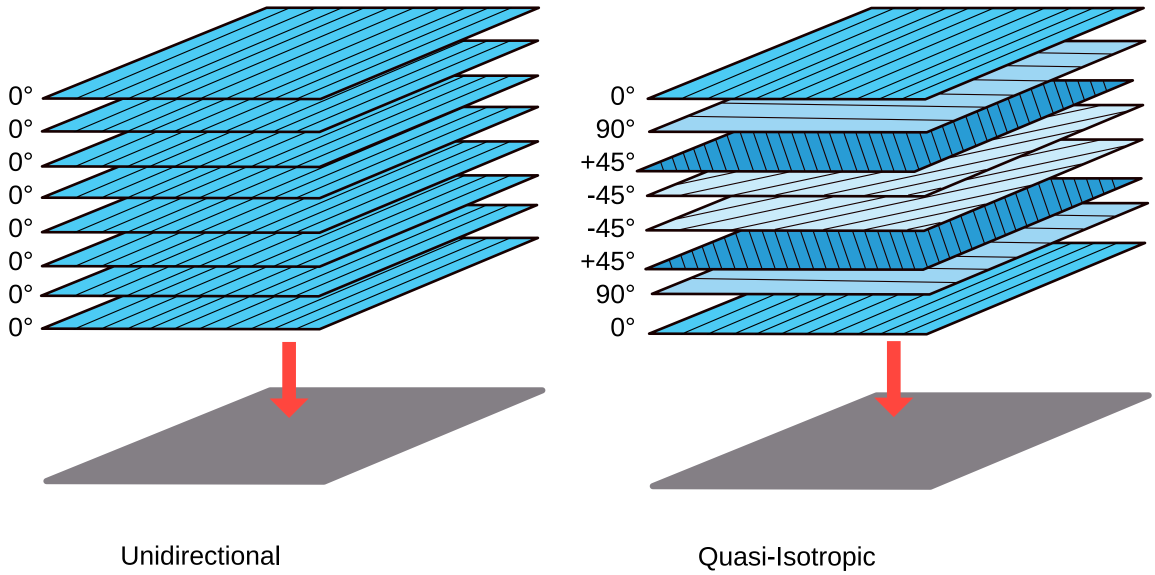


Fig. 3. Schematic representation of a laminate consisting of multiple UD plies. Image adapted from [1].

the choice of reinforcement fibre influences not only environmental impact and mechanical performance, but also manufacturing behaviour, handling, and achievable geometries. Vegetal and mineral fibres offer lower embodied energy, greater regenerative potential, and reduced dependence on fossil resources compared to conventional synthetic composites. Natural fibres such as flax and hemp are renewable and biodegradable [33–35], while mineral fibres such as basalt combine natural abundance with favourable mechanical performance [12].

Beyond their environmental characteristics, these fibres differ in surface texture, stiffness, bundle cohesion, and interaction with resin systems, leading to distinct processing requirements and material expressions during fabrication. As illustrated in Figure 2, vegetal, mineral, and synthetic fibres exhibit visibly different physical characteristics, which influence fibre placement, consolidation, and handling during manufacturing, as well as the resulting visual and tactile qualities of the finished frame. Although recyclability remains a challenge for composite materials regardless of fibre type, vegetal and mineral fibres provide a longer-term sustainability perspective while enabling alternative sensorial, visual, and tactile material expressions. Other natural materials, such as bamboo, have been discussed in the literature [10], but are not considered suitable here due to their limited compatibility with geometrically complex, performance-oriented frame architectures [14]. These material differences motivate an investigation into how fibre choice affects both manufacturing feasibility and perceived riding experience.

At the same time, current manufacturing practices impose significant constraints on the adoption of alternative materials. Many bicycle frames are produced using pre-impregnated (pre-preg) fibres, which require cold storage, careful handling, and labour-intensive manual lay-up. In these processes, frames are constructed by stacking multiple unidirectional (UD) composite plies, each consisting of fibres aligned in a single direction, to tailor stiffness and strength according to local load requirements (Figure 3).

To conform to complex frame geometries, flat pre-preg sheets must be cut into intricate shapes before lay-up, generating substantial material waste in the form of offcuts—unused remnants of composite material that cannot be reused once cut [29]. These inefficiencies increase environmental impact and limit experimentation with alternative fibres, as deviations from established lay-up schedules and ply architectures introduce additional cost, risk, and manufacturing uncertainty. This highlights the need for manufacturing approaches that can accommodate new fibres and laminate configurations without abandoning existing industrial knowledge, tooling, and structural design principles.

These process-level constraints are further reinforced by the global organisation of bicycle manufacturing. A large proportion of bicycle frame production by EU- and US-based brands is outsourced to Asia to reduce labour costs, distancing material choices and manufacturing decisions from local contexts. This globalised production model increases dependence on long-distance freight transport [2], contributing additional emissions; container shipping from Asia to Europe alone is estimated to produce 10–40 g of CO_2 per tonne-kilometre [26]. This situation is particularly notable given that road and gravel cycling is predominantly practiced in high-income regions where sustainability concerns are increasingly emphasised and where ambitious policy goals related to carbon reduction, circularity and localised production have been articulated. These tensions further motivate the exploration of manufacturing strategies that are compatible with regional production contexts.

In addition to logistical and organisational factors, the economic structure of carbon-fibre production reinforces this dependency. Carbon fibre remains an energy- and capital-intensive material, with production costs dominated by raw materials, energy consumption, and high investment in specialised equipment [15]. These characteristics limit supply flexibility and contribute to increasing material prices, limiting manufacturers' ability to relocate production or diversify supply chains. As a result, designers and engineers face a structural tension between the sustainability ambitions articulated at both policy and market levels and the realities of the contemporary bicycle frame manufacturing infrastructure. This context underscores the relevance of evaluating the perceived value and feasibility of alternative material solutions.

In response to these limitations, dry-fibre manufacturing approaches, such as filament winding, have emerged as promising alternatives. Filament winding is a semi-automated process that ensures consistent alignment of the fibres [24] while significantly reducing material waste—typically around 2–4% compared to 15–20% in manual lay-up processes [31]. Its ability to place fibres along load paths with minimal waste makes it particularly well suited to tubular structures such as bicycle frames. Recent developments, including removable and expandable mandrel systems, have further expanded its applicability to more complex geometries while maintaining flexibility in material selection [30]. These developments provide the technical foundation for the integration of vegetal and mineral fibres into industrially viable frame manufacturing.

Within this industrial context, regionally available vegetal and mineral fibres offer additional strategic advantages. The use of locally rooted materials has been shown to improve supply-chain resilience, reduce transport-related emissions, and strengthen the alignment between material sourcing, manufacturing, and regional industrial capabilities[32]. Italy provides a representative case study: industrial hemp has historically been cultivated in southern regions, particularly Sicily, for textiles, ropes, and sails [19], with renewed interest driven by its ecological and regenerative potential [36]. Similarly, basalt—abundant in the region surrounding Mount Etna—has long been used in architecture and infrastructure and is now available as a continuous fibre suitable for composite reinforcement [18]. These regional conditions inform the selection of flax, hemp, and basalt as candidate fibres in this study.

Previous research has demonstrated the basic manufacturability of natural-fibre bicycle frames, including hemp-reinforced composites combined with aluminium cores [9]. That work focused on simplified round-tube geometries and excluded dry-fibre manufacturing routes. Other studies have examined flax-based reinforcements in more complex geometries, although these were typically applied to isolated frame components rather than fully integrated structures and relied on pre-preg lay-up and secondary bonding processes [3]. Although capable of achieving high structural performance, such methods are labour intensive, costly, and limited in scalability [8]. Differences in fibre properties within hybrid laminates can also increase susceptibility to interlaminar stress concentrations and delamination under cyclic loading [16].

Moreover, much of existing research evaluates natural fibre bicycle frames primarily through laboratory-based mechanical tests [3, 9], without allowing direct interaction between the riders and the artefact. As a result, the influence of material choice and manufacturing process on user perception, tactile qualities, and riding experience remains underexplored. Prior work in product and material design suggests that the acceptance of natural-fibre composites is strongly shaped by sensorial qualities and embodied interaction [9]. This gap motivates a focus on rider perception and interpretation in real use.

1.1 Aim of the Study

To address this gap, the present study investigates whether a full-scale gravel bicycle frame can be designed, manufactured, and ridden using sustainable vegetal and mineral composite fibres while remaining compatible with contemporary industrial manufacturing constraints. The research explores the integration of flax, hemp, and basalt fibres within a dry-fibre composite workflow, adopting a design-through-making approach to bridge material development, fabrication, and real-world use. Beyond demonstrating technical feasibility, the study examines how cyclists experience and interpret these material and manufacturing choices during real riding. By producing a structurally functional and rideable prototype, research considers not only structural performance, but also rider perception, visual identity, material legibility, trust, and perceived value. In this way, the gravel bicycle frame is positioned both as a load-bearing structure and as an interactive artefact through which sustainability, performance, and material intent are negotiated in use. Consequently, the study is guided by the following research questions:

RQ1: How can a design-through-making approach integrate sustainable fibres (flax, hemp, basalt) into industrial manufacturing to produce a rideable, high-performance frame?

RQ2: How do cyclists perceive and interpret the riding experience of vegetal- or mineral-fibre frames compared to conventional materials?

RQ3: How do material choices and manufacturing processes shape the visual identity, legibility, and user trust of a sustainable gravel frame?

RQ4: What is the perceived value and commercial feasibility of a high-performance gravel bicycle made from sustainable composite materials?

2 DESIGN-THROUGH-MAKING: MATERIAL EXPLORATION

Fig. 4. 3T Extrema Italia frame showing the labelling convention and the division into front and rear triangles.

The *Extrema Italia* gravel bicycle frame was used as a reference artefact for this study. It represents a contemporary high-performance gravel frame and provides a realistic baseline for exploring the integration of alternative composite materials within industrial manufacturing constraints, while maintaining relevance to real-world riding conditions and user expectations.

The frame is designed for demanding riding scenarios, including rough gravel terrain, endurance riding, and bikepacking (self-supported multi-day cycling using lightweight frame-mounted luggage) applications involving additional carried mass. These use conditions informed the loading scenarios and performance requirements applied in this work, ensuring that material and manufacturing decisions were grounded in situations commonly experienced by riders.

Frame geometry was therefore treated as a fixed design parameter and was not explored as a variable in this investigation. To ensure consistent terminology when referring to structural components, Figure 4 presents the frame geometry and labelling convention used throughout this study. The frame is described in terms of a front triangle and a rear triangle connected by the seat tube; adjacent components such as the fork, seatpost, stem, and handlebars are referenced only when relevant to structural loading, manufacturing decisions, or rider interaction.

2.1 Composite Material and Manufacturing System

This study investigates fibre-reinforced polymer composites using continuous fibres, consistent with filament-wound bicycle-frame manufacturing. Continuous, aligned fibres were selected to ensure structural relevance, manufacturability, and consistency with numerical modelling, while also enabling material substitution and comparison within an existing industrial process. This approach allows alternative fibres to be explored without requiring changes in manufacturing equipment, tooling, or workflow.

Three categories of fibres were explored: carbon (synthetic), basalt (mineral), and vegetal fibres. Carbon fibre was used as a mechanical benchmark due to its widespread adoption in high-performance bicycle frames. Basalt fibres were considered for their intermediate stiffness, impact resistance, and lower embodied energy, while vegetal fibres were investigated for their potential damping behaviour and perceived sustainability—properties that can influence rider comfort, trust, and material acceptance in use.

Among the vegetal fibre options considered, hemp was initially selected as the reinforcement due to its renewable origin and regional relevance. However, at the time of prototype development, continuous hemp rovings with sufficient consistency and quality for reliable filament winding were not available from commercial suppliers. By contrast, flax (linen) rovings were available in consistent quality and exhibited stable processing behaviour suitable for filament winding. Flax was therefore selected for the physical prototype, while hemp was retained for comparative numerical exploration. This choice reflects a central aim of the study: to investigate how sustainable material integration can be achieved within current industrial constraints, adapting material selection to realistic availability and manufacturing reliability rather than relying on bespoke or experimental production routes.

The frame was manufactured using dry filament winding followed by resin transfer moulding (RTM). In filament winding, continuous rovings are deposited under controlled tension onto a rotating mandrel, enabling repeatable fibre placement and local tailoring of stiffness through winding angle. Importantly, the dry-fibre process allows different types of fibres to be selected, combined, or substituted at the time of winding. When hybrid configurations are required, multiple fibre types can be deposited simultaneously, providing material flexibility without altering the underlying manufacturing system.

Following winding, the dry fibre preforms were impregnated and consolidated using RTM. As illustrated in Figure 5, RTM involves placing the dry preform into a closed mould and injecting liquid resin under controlled pressure, allowing the resin to flow through the fibre network and cure to form a consolidated composite structure.

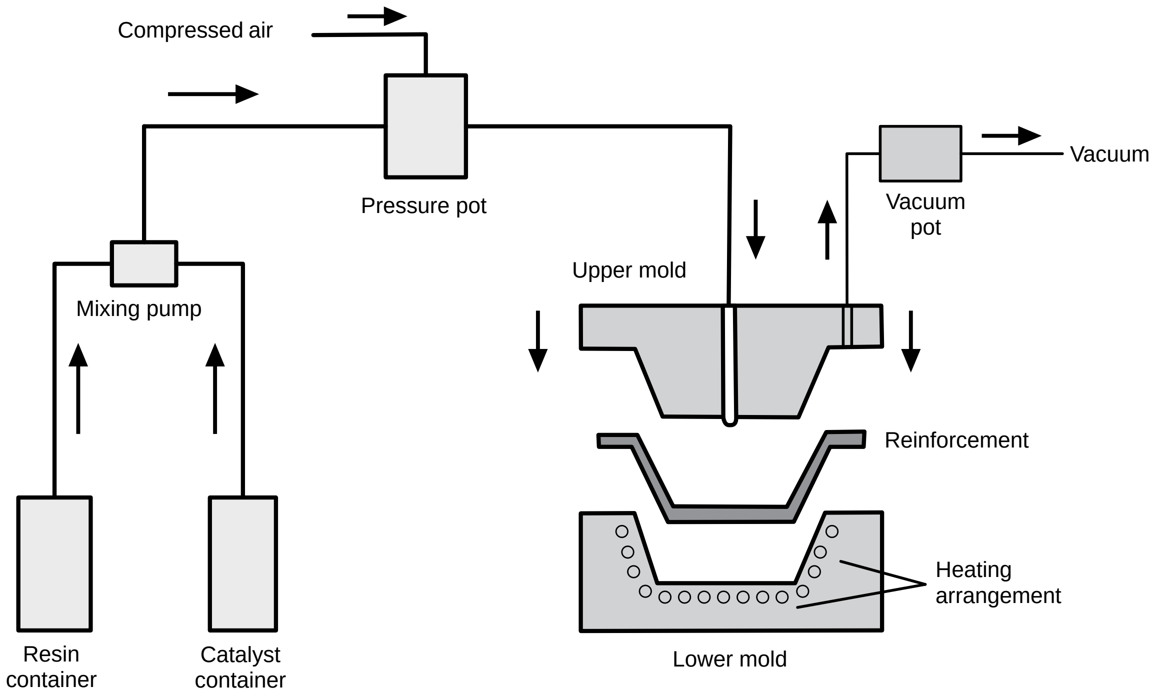


Fig. 5. Schematic representation of the resin transfer moulding (RTM) process.

RTM provides good surface quality, repeatability, and reduced void content compared to open mould processes. This manufacturing route reflects current industrial practice and imposes practical constraints on laminate thickness, fibre routing, and material combinations—ensuring that the resulting prototype remains representative of frames that could realistically be produced at scale.

Together, the selected material system and the manufacturing process define not only the structural behaviour of the prototype but also the physical conditions through which riders interact with the frame. The selection of fibres, the configuration of the laminates and the composition of the surface material directly influence the response to vibration, the visual appearance, and the legibility of the material. These characteristics shape how the bicycle is experienced, interpreted, and trusted by riders during real-world use.

2.2 Stiffness Testing as Experiential Reference

Mechanical testing was used to support the design-through-making process by establishing a quantitative performance reference against which rider experience, perception, and trust could be interpreted. Rather than serving as an exhaustive certification, stiffness tests were used to ensure that the prototype exhibited structural behaviour consistent with high-performance gravel bicycle frames, thereby enabling a meaningful interpretation of rider feedback.

In bicycle design, stiffness is a key parameter that links structural performance to rider experience. The stiffness of the bottom bracket (BB) is commonly associated with perceived pedalling efficiency and responsiveness, while the stiffness of the head tube (HT) influences steering precision, stability, and confidence. As such, stiffness values provide a measurable reference for understanding how riders perceive control, feedback, and overall ride quality during use.

In this study, the stiffness of BB and HT in the manufactured prototype was evaluated and compared with the predictions of the finite element method (FEM). This combined experimental–numerical approach served two purposes: first, to verify that the prototype fell within established industry-relevant stiffness ranges; and second, to provide a reference framework for relating rider perceptions to known structural characteristics. By situating the prototype within these ranges, rider responses could be interpreted relative to familiar performance benchmarks rather than as isolated impressions.

Although comprehensive frame qualification typically includes fatigue, impact, and additional static tests—often defined within DIN EN ISO 4210-6 [21] these were not experimentally reproduced within the scope of this work. Instead, selected ISO 4210-6 load cases were evaluated using FEM simulations to assess structural safety under representative extreme and long-term use conditions. This approach reflects common early-stage industrial practice, in which simulation is used to screen feasibility and contextualise physical tests prior to full certification.

Stiffness was evaluated using a widely adopted industry methodology based on controlled load application and displacement measurement. Two stiffness parameters were considered:

- Head Tube (HT) stiffness, representing resistance to torsional deformation during steering;
- Bottom Bracket (BB) stiffness, representing resistance to lateral deformation under pedalling loads.

In both cases, stiffness was defined as the ratio between applied force F and measured displacement U,

$$c = \frac{F}{U},$$

with replicated experimental configurations in the FEM environment to ensure comparability [5].

By establishing the prototype within established stiffness metrics commonly used in the bicycle industry, this testing framework provides a shared mechanical reference for comparison with other frames. This provides a mechanical reference against which rider perceptions, collected later in the study, can be interpreted. In doing so, stiffness measurements allow subjective riding experience to be discussed not only qualitatively but also in relation to established stiffness ranges, supporting the interpretation of how material and manufacturing choices influence both measurable performance and perceived ride quality.

2.3 Simulation as a Design Support Tool

FEM simulations were used as an exploratory design support tool within the design-through-making process to assess material feasibility and ensure rider safety prior to physical manufacturing. Rather than aiming for laminate optimisation or complete structural validation, simulations were used to compare the relative behaviour of different composite material systems under consistent loading conditions derived from ISO 4210-6.

This use of simulation enabled a reduction of the material design space before physical prototyping, allowing potentially unsafe or unsuitable material configurations to be identified and excluded early. In this sense, FEM functioned as a decision-support instrument that guided material and lay-up choices, ensuring that only configurations expected to fall within safe and rideable performance ranges were taken forward to fabrication.

The simulations were conducted using a simplified representation of the frame that captured the dominant structural behaviour relevant to the comparison of the material. Identical boundary conditions and load magnitudes were applied in all material configurations so that observed differences could be attributed to material choice rather than modelling assumptions. Selected ISO 4210-6 static load cases were used to represent extreme and long-term use conditions that could pose safety risks if not adequately considered prior to manufacturing.

By providing a consistent mechanical reference across candidate material systems, FEM simulations supported the development of a safe, rideable prototype and reduced the risk associated with introducing alternative fibres into a load-bearing bicycle frame. This simulation-based screening established a mechanical baseline against which subsequent physical testing and rider experience could be meaningfully interpreted.

2.4 Prototype Configuration and Frame Geometry

The prototype was manufactured in a size 54 configuration, corresponding to a mid-range frame size commonly used as a reference in bicycle development and prototyping. This size typically accommodates riders with heights of approximately 170–180 cm and is often the first geometry produced when evaluating new frame concepts, materials, or manufacturing processes. Selecting this size ensured compatibility with the majority of participants in the riding study, allowing differences in perception and experience to be primarily attributed to material and manufacturing choices rather than to geometry-related variation.

2.5 Manufacturing Constraints and Material Configuration

The initial design intent was to explore a frame configuration in which one carbon layer would be replaced by multiple vegetal fibre layers, allowing a more substantial integration of sustainable materials. However, this approach proved to be incompatible with the practical requirements of producing a safe and rideable prototype. Increasing the thickness of the laminate would have required new mandrels and geometry modifications, introducing uncertainty in both structural behaviour and safety of the rider.

To balance material exploration with the need for a reliable and interpretable riding experience, vegetal fibres were therefore integrated as an additional outer layer while retaining the existing carbon-based structural lay-up. This configuration allowed the use of established filament-winding tooling and ensured predictable structural behaviour, while still allowing investigation of how vegetal fibres influence aspects of the riding experience. Previous studies indicate that placing vegetal fibres on the outer surface can enhance damping behaviour, making this configuration particularly relevant to examine vibration perception without compromising structural integrity [16].

The rear triangle was left unchanged due to tooling and process constraints, as its components are manufactured as a single integrated assembly. Modifying this region would have required a complete redesign of the tooling and curing procedures, which would have introduced additional variables not related to the focus of the study material. By keeping the rear triangle unchanged, the study maintained a stable reference structure, supporting a clearer interpretation of rider feedback.

The material system investigated in this study comprises carbon, basalt and vegetal fibres, in accordance with the scope defined in RQ1. Carbon fibre was used as a structural reference material due to its widespread adoption in high-performance bicycle frames. Basalt fibres were selected for their intermediate mechanical properties and lower energy embodied compared to carbon. Within the category of vegetal fibres, flax was used in the physical prototype because of its availability in consistent, continuous rovings suitable for reliable filament winding. Hemp, while relevant from a sustainability and regional perspective, was therefore considered only at a numerical level.

The material properties used for the numerical evaluation were derived from supplier data and established literature. Rather than aiming for precise material characterisation, these properties were used to enable consistent comparison across material systems. The composite properties were estimated using standard analytical approaches and applied uniformly throughout the simulations to support the relative assessment of the behaviour of the material. Detailed material data and calculation procedures are provided in the supplementary material.

In general, the selected hybrid flax–carbon configuration represents a deliberate design compromise. It enabled the fabrication of a safe and rideable artefact while preserving the opportunity to study how the partial integration of vegetal fibres influences the mechanical response, vibration behaviour, and perception of the rider under real riding conditions.

2.6 Results of Stiffness Test

Physical stiffness tests were conducted on the bottom bracket (BB) and head tube (HT) to establish a mechanical reference to interpret rider experience and to verify that the manufactured prototype behaved consistently with expectations derived from the previous FEM screening. The average stiffness values measured were 175 N/mm in the BB and 27.5 N/mm in the HT, with low variability between repeated measurements.

These values fall within the ranges commonly reported for contemporary gravel bicycle frames. BB stiffness values are typically reported between approximately 160 N/mm to 200 N/mm, while HT stiffness values generally fall between 25 N/mm to 30 N/mm. The measured values therefore place the prototype within the established performance envelope of this category.

The integration of a flax outer layer did not result in stiffness values outside these expected ranges. Although the total frame mass increased by approximately 250 g, the stiffness of BB and HT remained comparable to those reported for conventional carbon gravel frames, indicating that the hybrid configuration did not introduce atypical structural behaviour.

The measured stiffness values showed moderate deviations from the FEM predictions, reflecting the expected differences between the simplified numerical models and the manufactured composite structures. Therefore, FEM was used to support comparative material assessment and structural safety screening rather than to predict absolute stiffness values.

Overall, the measured stiffness results situate the hybrid flax–carbon prototype within a mechanically familiar range for gravel bicycle frames. This establishes a stable reference condition for the subsequent riding study, allowing rider perceptions to be interpreted relative to known structural behaviour rather than being influenced by unexpected or safety-critical deviations in frame stiffness.

2.7 Design Implications

FEM simulations were used to explore the feasibility of vegetal, mineral, and hybrid composite material systems using high-performance bicycle frames as a reference case. High-performance frames impose particularly stringent requirements on stiffness, weight, and structural safety, making them a suitable stress case for evaluating the limits of alternative composite materials. The results indicated that purely vegetal-fibre configurations would require either increased laminate thickness or extensive hybridisation to achieve stiffness and safety levels comparable to conventional carbon-based references. Such thickness increases were not compatible with existing filament-winding tooling and would have introduced uncertainties related to manufacturability, structural behaviour, and rider safety.

In contrast, hybrid configurations demonstrated that partial integration of vegetal fibres—when combined with stiffer reinforcements—could approach the mechanical performance of carbon frames while remaining within established geometric and safety constraints. These findings directly informed the decision to limit vegetal-fibre integration in the physical prototype to a single flax layer, rather than pursue a full or multi-layer substitution.

The position of flax as an outer layer was a deliberate design choice. The results of FEM and previous experimental studies indicate that the placement of the outer-layer allows vegetal fibres to contribute to vibration damping and surface compliance without significantly altering global frame stiffness. In particular, previous work has shown that when flax is used as an external layer, the damping ratio can increase by 53.6% with a single flax layer and up to 94% with two outer flax layers [16].

On this basis, the integration of a single flax outer layer was considered sufficient to introduce a meaningful increase in vibration damping likely to be perceptible to riders, while avoiding the increased laminate thickness, mass, and manufacturing risk associated with multiple vegetal layers. Placing flax as the outermost ply primarily targets material properties relevant to rider comfort and vibration perception—specifically increased internal damping, reduced high-frequency vibration transmission, and altered surface compliance—while preserving a familiar and predictable global stiffness response consistent with high-performance gravel bicycle frames.

On this basis, flax fibres were selected as vegetal reinforcement for the prototype, balancing mechanical feasibility, manufacturing reliability, and experiential relevance. The FEM study was not used to optimise the laminate architecture, but rather to define a safe and realistic design envelope within which user perception, comfort, and acceptance could be meaningfully studied. By limiting flax integration to a single outer layer, the prototype remained representative of a high-performance gravel bicycle configuration that riders could plausibly encounter, rather than an experimental structure with atypical stiffness characteristics.

Beyond rider experience, the results also suggest broader implications for composite manufacturing practice and occupational health. Partial substitution of carbon fibres with vegetal fibres can reduce the extent of carbon fibre handling during winding, trimming, sanding, and finishing operations. Carbon fibres are associated with well-documented occupational health concerns, particularly related to the release of fine filament fragments and respirable airborne dust during cutting, machining and post-processing. Prolonged exposure to such particulates has been associated with skin irritation, respiratory discomfort, and the need for stringent protective measures in composite manufacturing environments.

Although worker exposure was not directly quantified in this study, the integration of vegetal fibres—particularly when placed as outer layers—suggests a potential reduction in direct contact with carbon fibres during downstream manufacturing steps. Vegetal fibres generally break down into larger and less respirable particles and exhibit different fragmentation behaviour during machining, which can reduce the generation of fine airborne debris. As such, hybrid laminate configurations that limit the exposure of carbon fibre on the surface could contribute to improved working conditions while remaining compatible with existing industrial processes.

These considerations point to an additional, often overlooked dimension of sustainability in composite bicycle manufacturing, which extends beyond material sourcing and environmental impact to include worker safety and production ergonomics. More targeted investigation would be required to quantitatively assess exposure levels and validate these potential benefits.

Together, these findings highlight that material choices in a design-by-design context extend beyond structural performance alone. Decisions about the extent and placement of vegetal fibres influence rider comfort, perceptual qualities, and trust, while also shaping manufacturing conditions and occupational safety. Sustainable material integration should therefore be understood as a socio-technical design challenge, linking user experience, production practice, and environmental responsibility.

3 USER PERCEPTION STUDY

A user study investigated how riders perceive the hybrid carbon–flax frame under real riding conditions. Subjective evaluations of comfort, stiffness, confidence, and overall ride quality were combined with objective ride and vibration measurements to contextualise the user experience. The inclusion of sensor-based data was intended to support, rather than replace, riders' self-reported perceptions by linking felt ride qualities with measurable on-road behaviour. The study was conducted around Eindhoven, the Netherlands and Düsseldorf Germany between 27 October 2025 and 30 November 2025.

3.1 Method

3.1.1 Participants. A total of 13 experienced cyclists participated in the user tests. Eight participants were recruited from Squadra Veloce team of Eindhoven University of Technology (https://www.squadraveloce.nl), and five participants were recruited through personal networks. The ages of the participants ranged from 19 to 54 years, with a median age of 22 years (M = 29.3, SD = 12.8). The group consisted of nine male and four female riders.

The' heights of the participants ranged from 171 cm to 185 cm, with a median height of 178 cm (M = 178.2 cm, SD = 4.8 cm). The heights of the male participants' ranged from 171 cm to 185 cm, with a median height of 180 cm (M = 180.0 cm, SD = 4.7 cm). The heights of the female participants' ranged from 171 cm to 178 cm, with a median height of 174.5 cm (M = 174.5 cm, SD = 2.9 cm).

The cycling frequency during the last 12 months was generally high. Six participants cycled 1 to 3 days per week, five cycled 4 to 6 days per week, and one participant reported cycling every day. The self-rated cycling experience was high, with a mean score of 4.08 out of 5 (SD = 0.86). The annual distance covered varied widely. Five participants rode between 1 and 1,000 km per year, three rode 1,001 to 5,000 km, four rode 5,001 to 15,000 km, and one participant exceeded 20,000 km. The majority of the riders mainly used the road bicycle (7 participants) and the mountain bicycle (7 participants), with gravel riding also common (5 participants). Familiarity with frame materials showed a moderate mean score of 3.38 out of 5 (SD = 1.04), indicating that most of the participants had at least some understanding of the differences between aluminium, carbon, steel, and composite constructions. The cost of the ' current primary bicycles of the participants ranged widely, with most between €1,000 and €5,000, and two more than €7,500. Most of the participants reported bicycle weights between 7 kg and 9 kg (9 out of 12 valid responses). Specifically, four participants reported weights between 7 ˘8 kg, five between 8 ˘9 kg, and two between 9 ˘10 kg. One participant reported a bicycle weight above 10 kg, and one participant indicated that they did not know the weight. When asked about factors that influence frame choice, participants rated stiffness, comfort, durability, handling, and weight as the most important considerations, while sustainability and cost showed more varied responses. This suggests that the sample consisted of riders who were performance-orientated but still aware of material and environmental aspects, making them well suited to evaluate the mechanical and perceptual qualities of a hybrid carbon–flax gravel frame.

3.1.2 Procedure and the Bicycle Setup. Before the riding session, each participant completed a pre-test questionnaire to collect information on cycling experience, preferred riding style, and familiarity with different frame materials. These questions were adapted from the work of Bazilinskyy et al. [6]. After this stage, each participant received the test bicycle, which was equipped with a set of instruments for data collection. The study received ethical approval from the Ethics Review Board of the Eindhoven University of Technology, and all participants gave their informed consent prior to participation.

A Garmin Edge 540 Solar bicycle computer was mounted on the handlebar to record riding data during the study. The device logged speed, route, elevation, ambient temperature, and gear-shift events using its integrated multi-band GNSS (GPS) satellite positioning system. Data were recorded at a temporal resolution of approximately one sample per second, using the device's default recording settings. Road surface types were also captured through the recorded GPS track and subsequently classified during post-processing. In addition, a Samsung Galaxy S10+ smartphone was rigidly mounted to the handlebars to record vibrations experienced during the ride using its internal accelerometer, along with time and GPS data. Vibration signals were recorded at the maximum available sampling rate of 122 Hz using the Sensor Logger application, ensuring sufficient temporal resolution to capture road-induced vibration content during real-world riding. The bicycle was assembled with a Selle Italia Novus Boost Evo Superflow 145 saddle, an Apto Stealth 80mm stem, and an Aereoghiaia Integrale carbon handlebar. The drivetrain used an SRAM Rival AXS 2022 wireless electronic groupset with hydraulic disc brakes and a 1x drivetrain configuration consisting of a 40-tooth chainring and a 10–44 cassette. The wheels were Fulcrum Rapid Red 900 paired with Continental Race King 29",×,2.0 new tyres, providing a reliable balance between traction and rolling resistance for mixed-surface testing. The total weight of the bicycle used for user testing, including Shimno SPD pedals, was 8.5 kg.

All participants received a certified Massi helmet and received a short safety briefing before starting the test. The briefing emphasised that the ride would take place in a real-world traffic environment and that participants were required to comply with all applicable traffic regulations at all times, as the study did not involve racing or competitive riding. Each rider was allowed to choose their own route to replicate realistic cycling conditions **??**. The recorded routes were anonymised after data collection for the purpose of submission. Upon completion of the ride, participants completed a post-test questionnaire to evaluate their perceived comfort, stiffness, and overall riding experience.

Fig. 6. User testing session conducted on unpaved terrain to evaluate rider perception, comfort, and vibration response under real riding conditions.

After the ride, all participants were required to complete a post-test questionnaire, which included questions about the frame and the bicycle setup, as well as items that focused on their overall riding experience. See supplementary material 5 for the materials used in the study.

3.1.3 Data Analysis. A Python script was used to synchronise Garmin activity data with smartphone accelerometer recordings, allowing vibration, speed, and road-surface conditions to be analysed on a shared timeline. Signal filtering and peak-detection techniques were applied to extract dominant vibration frequencies and root mean square (RMS) acceleration values, which provide a measure of the overall magnitude of vibration experienced over each road segment. The responses of the questionnaire were then merged with the performance data to allow a comparison between the behaviour of the objective frame and subjective perceptions of the users. The analysis script is provided in the supplementary material (see Section 5).

3.2 Results

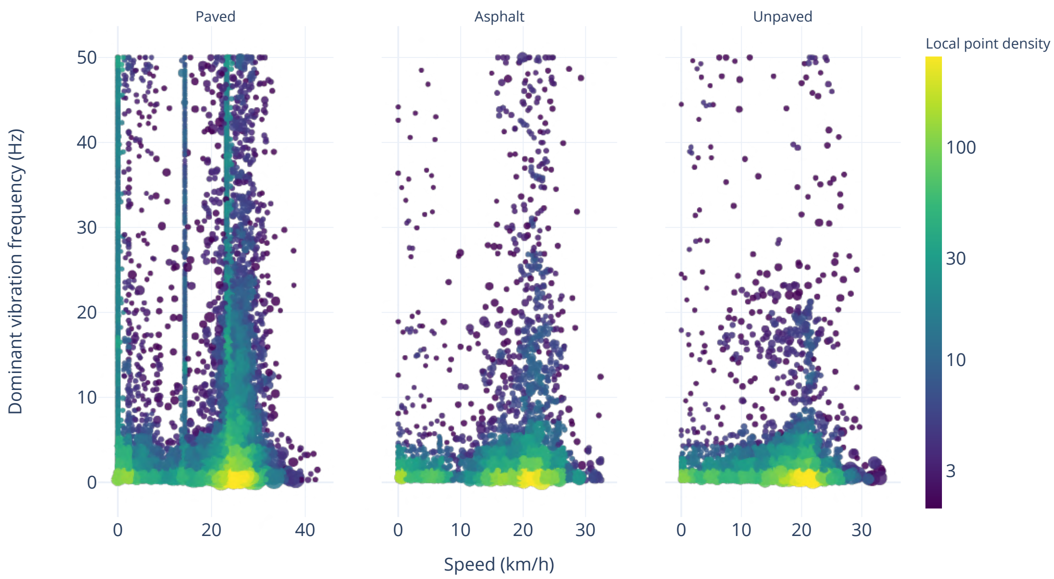


Fig. 7. Dominant vibration frequency versus cycling speed across different surface types. Individual points represent vibration events, with colour indicating local point density.

Across all recorded routes, the cyclists covered a total distance of 352.89 km. The distribution of road-surface types indicates that the majority of riding occurred on paved surfaces (133.06 km, 37.7%) and asphalt (121.84 km, 34.0%), followed by unpaved terrain (67.43 km, 19.1%). The smaller portions of the distance were classified as unknown (18.94 km, 5.4%) or natural surfaces (11.62 km, 3.3%).

Anonymised results are available in the supplementary material 5. The overall average cycling speed among all participants was 19.5 km/h, with a recorded maximum instantaneous speed of 43.9 km/h. Elevation changes during the rides were minimal, with a total elevation gain of 15.2 m and a total elevation loss of 78.8 m. On average, each ride resulted in an elevation gain of 1.2 m and an elevation loss of 6.1 m. The mean ambient temperature recorded during the rides was 8.7 °C, with a minimum of -1.0 °C and a maximum of 26.0 °C. The unusually high maximum temperature is likely attributable to the start of certain rides that take place indoors, before participants move outdoors.

To contextualise riders' comfort and stiffness evaluations, vibration behaviour was analysed across surface types and speeds encountered during the rides. Figure 7 illustrates the relationship between cycling speed and dominant vibration frequency across all participants, with data separated by surface type. Individual vibration events are plotted as points, with colour intensity indicating the local density of observations in the speed–frequency space. Across all surfaces, the majority of vibration events cluster within the

2–20 Hz range at typical riding speeds of approximately 15–30 km/h, corresponding to the frequency band most perceptible to cyclists. Paved and asphalt surfaces exhibit a higher concentration of low-frequency vibrations with a relatively narrow spread, reflecting smoother and more consistent riding conditions. In particular, the data on the pavement surface reveal distinct vertical clusters at specific frequencies that remain largely constant across a wide range of cycling speeds. The appearance of these discrete frequency bands is consistent with the finite frequency resolution of the windowed Fourier analysis applied under relatively steady-state riding conditions, particularly on paved surfaces. Under such conditions, dominant vibration components are repeatedly assigned to the same frequency bins, leading to visible clustering in the speed–frequency space. Although system-level resonant behaviour cannot be fully excluded, the observed pattern is likely influenced by signal-processing characteristics rather than by speed-dependent structural excitation.

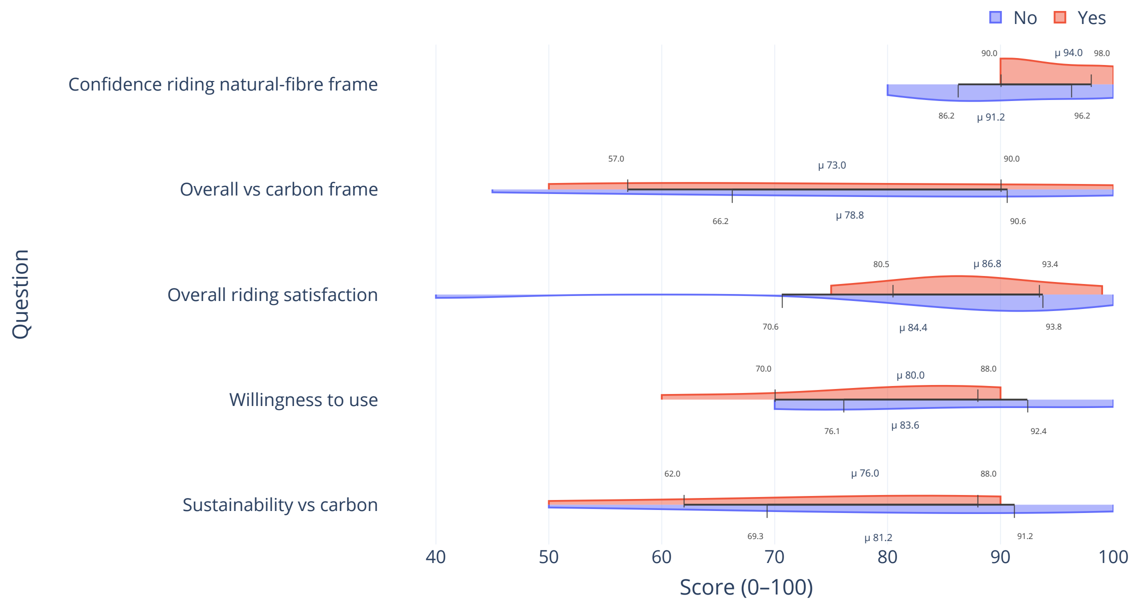


Fig. 8. Ratings for sustainability, willingness to use, satisfaction, performance compared to carbon, and confidence riding the frame, split by whether a fibre-related difference was perceived.

The results of the user tests indicate that the hybrid carbon flax frame delivered a riding experience that participants generally rated as equal to or better than that of their usual bicycles. Comfort on smooth surfaces received consistently high scores, while comfort on rough terrain showed greater variation but remained overall positive. Stiffness and responsiveness were positively evaluated, and riders reported stable handling during steering, cornering, braking, and acceleration. When asked to compare the prototype with a conventional carbon frame, most of the participants placed their ratings slightly above the "equal performance" midpoint, suggesting that the incorporation of vegetal fibres did not reduce perceived performance and may even have been interpreted as an improvement. Sustainability and innovation were highly rated throughout the sample and appeared to contribute positively to overall impressions. In the post-test questionnaire, the willingness-to-pay values centred around €4,000, aligning with expectations for a mid- to high-end gravel bicycle and indicating that the concept was viewed as commercially viable. In general, the prototype met user expectations for comfort, stiffness, and ride quality while fostering a positive perception of its sustainable material composition.

The average perceived weight score was 8.8 out of 10, indicating that most of the participants considered the frame relatively light. The scores were generally consistent among the participants, with the exception of one notably low score (1.5). This outlier is likely attributable to a misunderstanding of the question, as the participant may have interpreted it as referring to absolute frame mass rather than to a subjective assessment of perceived lightness.

Figure 8 provides more insight into how material perception shapes user evaluation. Participants who reported perceiving a fibre-related difference in the frame consistently gave higher ratings on measures of sustainability, willingness to use the frame, overall satisfaction, and confidence while riding. Importantly, this effect was observed despite the vegetal fibre being present only as a single outer layer, suggesting that the user's evaluation was not driven by the quantity of sustainable material, but rather by its visibility, meaning and perceived intent. In contrast, participants who did not perceive a material difference showed lower and more variable ratings, indicating weaker engagement with the material narrative.

Together, these findings suggest that user satisfaction and adoption potential are influenced not only by mechanical performance, but also by how material choices are perceived, interpreted, and trusted. Even limited integration of sustainable fibres can positively shape willingness to use and perceived value, demonstrating that material meaning plays a significant role in user experience alongside measurable ride qualities.

4 DISCUSSION

This study was set out to examine whether sustainable fibres, specifically flax, hemp and basalt, could be integrated into a high-performance gravel bicycle frame using filament winding and RTM, and how this approach compares with conventional carbon fibre construction. Rather than treating sustainability as a purely material substitution problem, the study combines numerical simulation, manufacturing constraints, and rider evaluation to assess feasibility within a realistic industrial production context.

FEM simulations and subsequent physical testing indicated that sustainable fibre composites can achieve stiffness behaviour comparable to conventional carbon frames when designed within appropriate structural and manufacturing constraints. While purely vegetal or mineral laminates would require substantially increased thickness to reach the stiffness levels associated with high-performance gravel frames—introducing manufacturing and experiential trade-offs—hybrid configurations combining flax with carbon offered a more viable balance between structural performance and material substitution [25].

Upon confirmation that the manufactured prototype fell within the established stiffness ranges of BB and HT, the simulation and testing phase established a stable mechanical baseline for the riding study. This ensured that rider perceptions of comfort, vibration behaviour, and overall ride quality could be interpreted without confounding effects arising from atypical stiffness. In this sense, simulation functioned not only as a feasibility check but as an enabling step for meaningful user evaluation, supporting the integration of sustainable fibres through a design-through-making approach (**RQ1**), in line with the prior work by Amiri et al. [3].

Manufacturing constraints further shaped the prototype configuration in ways that directly influenced user evaluation. The existing 3T filament-winding process could integrate flax only as an outer layer without requiring new mandrels, redesigned joints, or modified winding paths. This constraint informed the decision to limit the integration of vegetal fibres to a single outer layer, preserving predictable structural behaviour while targeting vibration damping and perceptual qualities most relevant to riders. As a result, the prototype remained representative of a high-performance gravel bicycle that users could plausibly encounter, strengthening the validity of the riding study and supporting the scalability considerations addressed in (**RQ4**).

The physical stiffness tests of the prototype confirmed that the integration of flax, even in limited quantities, does not compromise structural performance. Based on the test loads applied, the derived stiffness values were approximately 175 N/mm in the lower bracket and 27.5 N/mm in the head tube, which fall within the range typically reported for high-performance carbon gravel frames. Differences between stiffness values predicted by simulation and those measured experimentally reflect expected modelling limitations, particularly simplified joint representations and the inherent variability of natural-fibre composite lay-ups. Importantly, these differences were not substantial enough to alter the overall stiffness behaviour of the frame, establishing a stable mechanical baseline for the evaluation of the rider and supporting the feasibility of the design-through-making approach (**RQ1**).

Although flax is often associated with improved damping behaviour, the vibration analysis conducted in this study did not reveal a clear improvement at the system level (**RQ2**). The overall vibration response experienced by the riders was likely dominated by the tyres, wheels, and contact points of the rider, masking any subtle frame-level effects introduced by the flax layer. Previous material-focused studies showing that externally placed flax layers can increase damping ratios at the component level by up to

53.6% [16]. Thus, study highlights a critical insight for user experience: material-level performance gains do not necessarily translate into perceptible differences during real-world riding. For riders, acceptance and positive evaluation appear to depend less on measurable damping improvements and more on perceived ride stability, confidence, and trust in the artefact.

Despite the fact that the integration of flax did not reduce the overall amount of petroleum-based carbon fibre in the frame, cyclists evaluated the hybrid carbon–flax prototype positively. Comfort, perceived stiffness, handling, and overall ride quality received favourable ratings, with riders consistently describing the prototype as comparable to or better than their usual bicycles. These findings directly address **RQ2**, demonstrating that the inclusion of sustainable fibres—even when applied as an additive rather than a substitutive layer—does not negatively affect rider satisfaction or confidence.

Importantly, the results do not suggest that the prototype constitutes a fully sustainable alternative to conventional carbon frames. Rather, they indicate that partial integration of vegetal fibres can be achieved without compromising rider experience, thereby lowering barriers to future material substitution. Participants who reported perceiving a material-related difference tended to evaluate the frame more positively overall, suggesting that the rider experience is shaped not only by physical sensations but also by material awareness, expectations, and value alignment. This finding links perceptual outcomes to both **RQ2** and **RQ3**, highlighting the role of material legibility and trust as mediating factors in how sustainability-oriented material choices are interpreted in use.

From an industrial perspective, these results suggest that meaningful progress towards more sustainable composite frames does not necessarily require immediate or complete substitution of carbon fibres. Instead, partial integration of vegetal fibres can serve as a low-risk entry point that preserves familiar performance characteristics while allowing manufacturers to explore alternative materials within existing production systems. This approach offers strategic flexibility: material compositions can be incrementally adapted in response to supply availability, regulatory pressure, or sustainability targets, without requiring fundamental changes to tooling or manufacturing infrastructure.

From a commercial standpoint, such incremental integration can also help limit upfront investment and process risk compared to full material substitution, potentially mitigating the cost volatility associated with carbon fibre supply and allowing manufacturers to experiment with alternative fibres without committing to wholesale changes in production.

The frame mass further connects user acceptance with market feasibility. The total mass of the bicycle was approximately 8.5 kg (±100 g), with the frame alone weighing approximately 1.2 kg (±50 g), representing a modest increase compared to typical high-end carbon gravel frames. From a user perspective, participants did not report that the frame was noticeably heavier and were generally able to estimate its weight accurately, indicating that this increase did not negatively affect perceived quality or satisfaction (**RQ2**). Willingness-to-pay values remained aligned with expectations for the mid- to high-end gravel bicycle segment, suggesting that riders viewed the sustainable material choice as acceptable and commercially viable rather than as a compromise.

Taken together, these results indicate that the hybrid carbon–flax frame is suitable for real-world riding and use within its intended performance category. Although the sustainability contribution of the prototype lies in partial rather than complete material substitution, the findings demonstrate that such transitional material strategies can be implemented without undermining user acceptance, perceived value, or functional performance. In this sense, the prototype represents a viable step towards more sustainable composite bicycle frames that balances immediate usability with longer-term material transition goals, directly addressing **RQ4**.

4.1 Limitations and Future Work

Methodologically, the study was conducted under real-world riding conditions, which inevitably introduced external variables such as weather, road-surface variability, wind state, tyre pressure, and route choice. Although these factors limited experimental control, they also reflect the contexts in which gravel bicycles are typically used. The reliance on smartphone-based sensors constrained the isolation of frame-level damping behaviour; however, this setup supported an ecologically valid evaluation of rider experience. More controlled and instrumented testing protocols could complement this approach in future work, particularly where the objective is to isolate subtle vibration effects under repeatable conditions.

Participant recruitment was intentionally broad due to the limited number of participants that could be recruited within the scope of the study, and no prior selection was applied based on competitive or professional cycling background. Although a larger sample size and a more granular classification of participants would improve statistical power and allow subgroup analyses, the resulting participant profile aligns with the intended user base of gravel bicycles, which spans recreational, enthusiast and semi-performance riders, rather than elite competitors. Although the relatively small sample size (N = 13) limits the generalisability of the findings, it remains appropriate for an exploratory design-through-making study focused on user perception and early indications of market relevance, supporting the evaluation of commercial feasibility addressed in **RQ4**.

From a commercial perspective, willingness-to-pay results should be interpreted as indicative rather than predictive. The values reported in the post-test questionnaire clustered around €4,000, consistent with expectations for the premium gravel-bicycle segment. These responses reflect perceived value under test conditions rather than confirmed purchasing behaviour. Nevertheless, the absence of resistance to vegetal fibres and the positive association with sustainability provide insight into how users frame value and acceptability when evaluating alternative material choices, informing the interpretation of **RQ4**.

The research also highlighted the practical constraints inherent to the early-stage design-through-making. The degree of integration of flax in the prototype was primarily limited by existing tooling rather than material capability, while vibration measurements were constrained by consumer-grade sensing and uncontrolled test conditions. Similarly, FEM simulations relied on simplified joint representations, which are appropriate for comparative assessment but limit absolute predictive accuracy for natural-fibre composite structures. These constraints do not undermine the feasibility of the approach; rather, they define the current scope and resolution of the investigation and point directly to avenues for future development.

One notable limitation is the absence of a complete life-cycle assessment (LCA) of the proposed material system. Although vegetal and mineral fibres are often associated with lower embodied energy and improved environmental profiles compared to synthetic carbon fibres, these aspects were not quantified in this study. Factors such as laminate thickness, resin content, manufacturing energy, tooling requirements, durability, and end-of-life treatment may significantly influence overall environmental performance. Consequently, sustainability claims should be interpreted qualitatively, focussing on material potential and design flexibility rather than quantified environmental benefit. Future work should therefore prioritise a comprehensive LCA to enable a more rigorous evaluation of environmental impact.

Looking ahead, further work could expand the role of vegetal and mineral fibres through redesigned laminate architectures that strategically increase the flax content while maintaining the target stiffness and strength. Achieving this would require the development of new mandrels and filament-winding paths capable of accommodating thicker or more complex lay-ups, enabling deeper material substitution within industrially relevant manufacturing systems. More advanced experimental testing—such as professional tri-axial accelerometry, controlled tyre-pressure monitoring, and laboratory-based vibration rigs—would complement real-world riding evaluations by enabling clearer separation of frame-level and system-level behaviour. Long-term durability studies, including fatigue, impact, and environmental ageing tests, are also essential to validate natural fibres in load-intensive cycling applications.

Finally, broader market-oriented studies could investigate production costs, scalability, and willingness to pay among more diverse rider populations. Integrating economic modelling with LCA, mechanical testing, and user-experience data would support informed decision-making for industrial adoption and further extend insights related to **RQ1** and **RQ4**.

5 SUPPLEMENTARY MATERIAL

Supplementary material containing the code, the questionnaire and anonymised experiment data is available at: https://drive.google.com/drive/folders/1t-zu1Ldfz2wg0s3kh91LO1v7o97LXnhS

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