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Creating a Circular Design Workspace: Lessons Learned from Setting up a “Bio-Makerspace”

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Abstract: In today’s industrial short-lived products, long-lasting materials are often implemented (e.g., oil-based plastics for throwaway packaging). Circular economy teaches the importance of keeping these materials in use, as well as designing end-of-lives that regenerate natural systems. Designers can help drive to a circular transition, but are they ready for this challenge? Educating young designers on circularity seems a fundamental first step, including knowing and meaningfully using circular, bio-based and biodegradable materials. This substantiates the decision to expand the UGent Campus Kortrijk Design workspace to include specific technologies for circular, bio-based and biodegradable materials as a means of experiential learning during the prototyping phase. This paper reports on setting up a “bio-makerspace” as well as the use, adaption and redesign by 45 students. Qualitative data on work dynamics, used tools, materials, barriers and enablers were captured and analyzed to potentially facilitate the implementation of similar “bio-makerspaces” in different institutions. The next steps include the expansion and intensification of the use of the lab, in conjunction with the education of students to meaningfully match these materials to sustainable applications beyond the prototyping phase.

Keywords: circular economy; circular design; circular materials; design workspace; prototyping; bio-makerspace; bio-based materials; DIY-materials



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1. Introduction

Academic discourse, general press and social media are increasingly pointing out the critical and unbalanced synergies between humankind and the environment [1]. This results in an urgent call for an effort to use our limited resources more sustainably in order to meet current and future generations’ needs [2]. Lately, a growing amount of research and development is being conducted from various disciplines aiming at making the mechanics on which our society lives more sustainable [3]. Several studies focus on the impacts deriving from the industrial sector; these look at all industrial activities, from the extraction and use of materials to the methodologies through which products are created and manufactured, and from the economic models that sustain value exchanges to the users’ behaviors during use and consumption.

All these activities can broadly relate to design, where “design” is intended in its core meaning of “the act of creation of what does not yet exist but is ought to be” [4]. Specifically, Design for Sustainability (D4S) is the broad set of methodologies that focuses on creating more sustainable futures. One example of D4S is the consideration—from the initial design phases—of the entire life cycle in several ways, among which, striving for aligning the material lifespan with the product lifespan [5]. In fact, we often witness products with a short product lifespan (e.g., a disposable shopping bag might be used a few minutes only) made out of materials with a long material lifespan (e.g., the oil-based plastic of the bag

can last several centuries). This results in an “over-dimensioning” of the material with respect to its application, as shown in Figure 1. As a result, these *over-dimensioned* products produce waste that can either be recycled, valorized into energy, located in landfills or even dispersed in nature; all end-of-life scenarios that imply energy use, pollution and downgrading of materials qualities [6]. In this view, the material at hand should always be chosen according to the projected requirements, which must include the envisioned lifespan of the specific application [7,8]. To continue in the example, while some oil-based plastics are not an environmentally sustainable material choice in the context of a disposable shopping bag, they can, however, be considered a sound choice for a long-lasting reusable shopping bag [9,10].



Figure 1. Time-in-use versus material lifespan, often resulting in a mismatch and so a material over-dimensioning.

Growing attention is given to the possibility of using bio-based materials for achieving better end-of-life scenarios [11]. These materials can be bio-based circular materials (e.g., from the waste of food production or after consumption) and biodegradable at the end of life. Examples of these materials, reported later in the State-of-the-Art, are numerous yet often still in an early stage of development. Important to note is that D4S is much more extensive than just designing with *other* materials or *other* technologies. D4S should rather be seen as a sociotechnical system-level approach to the design of new product–service systems [12]. In this paper, we started specifically from the bio-based materials (the technological component) by implementing them into the design curriculum of UGent Campus Kortrijk (the social component). We then observed the systemic interactions between the different components, as later described.

In the next section, we moved from introducing the DIY, bio-based and circular materials to highlighting the role of designers and their education in the transition to a circular economy. Finally, we introduced the concept of design workplaces and specifically “bio-makerspace” as a physical place where design students can learn about these new materials.

2. State of the Art

A Circular Economy (CE) suggests the transition from the current *throwaway economy* to one where the very concept of waste is eliminated, resources are circulated and nature is regenerated, giving us the tools to fight climate change and biodiversity loss together, whilst addressing some important social needs [13]. A CE envisions several strategies to “close loops” by focusing on two main material flows: the technical and the biological ones. Our study focuses on the latter.

2.1. DIY, Circular and Bio-Based Materials: Examples and Impact

Biological streams can be valorized through different strategies, among which the *biorefinery* concept and the consequent creation of new materials. Bio-based materials are therefore derived from biomass being either waste (from production or after use) or virgin and can be characterized by various degrees of biodegradability at their end-of-life. Although not new as a class of materials, bio-based materials are gaining increasing interest for their potential benefits and role in a Circular Economy [14,15].

Industrially speaking, the sector that most implements bio-based materials nowadays is the building sector. Here, bio-based materials are used to insulate, cover and also take up structural tasks in buildings. Examples are made of hemp or flax fibers, wood waste and general lignin-based fibers, cork, mycelium-based materials and others. In order to

form panels, the fibers or particles might be pressed and heated together or mixed with organic or inorganic matrices [16]. Another well-developed sector is one of bio-based plastics, seen as a promising substitution of the oil-based ones. Examples of bio-based and biodegradable plastics derived from natural ingredients (e.g., starch from corn or potatoes) and/or oils. Examples are PLA, PBS and PHA [17]. Several publications explore the environmental benefits, as well as the emerging challenges, of producing and using these bio-based alternatives. Although lack of data and high variability between contexts should be taken into consideration, we can state that the main advantages can be summarized as the use of renewable resources (often from waste) and the better end-of-life scenarios that include industrial biodegradability and compostability [18,19].

Nevertheless, in the field of industrial design, only a few companies already propose solutions at an industrial level (e.g., Notpla creates packaging in seaweed-based 100% biodegradable materials; Mogu proposes mycelium-based architectural elements as tiles and soundproof panels; Circular Matters[®] creates plant-derived material panels) [20–22]. These solutions are accompanied and sometimes the results of a flourishing amount of experimental bio-based and circular alternatives that often remain on a DIY level. A DIY material is created locally with techniques and tools that the creator often invents through a process that can be individual or collective [23]. These alternative materials are made public by young designers, often using a platform where the “recipe” of the material can be found. Examples of materials are self-grown mycelium-based composites and bacterial leather, composites including wood, shells or other particles as filler and agar-agar or alginate as a binder (both deriving from algae). These materials and their recipes can be found on these platforms: materiom.org, diy-materials.com (accessed on 10 February 2021) and others [24,25]. The latter, more experimental and emergent category, is the one we experimented with in this paper.

Earlier research already put an emphasis on the exploratory behavior of today’s designers with regard to the creation of new materials through techniques and processes of their own invention, which is referred to as Do-It-Yourself (DIY) materials [23]. They can be entirely new materials, modified or further developed versions of already existing materials. By considering those emergent materials, some most prominent in the DIY, circular and bio-based materials are leather-like bacterial cellulose, 3D printing a ceramic-like material from eggshells, mycelium and many more [26,27]. The next paragraph explores the role that design and education can have in further exploring and experimenting with these materials.

2.2. *The Role of Design and Design Education in the Circular Economy of Biomaterials*

We often read that in order to transition to a CE, we must “design out waste and pollution”, putting design at the center of the discussion [28]. Consequently, the Ellen MacArthur Foundation sketches a “Circular Design Process” which consists of four stages and is informed by approaches such as design thinking and human-centered design [29]. Moreno et al. developed the conceptual “Circular Design Framework” to connect circular design business models with corresponding design strategies, with the purpose of supporting designers in achieving circularity [30]. In the broad realm of Design for Sustainability (D4S), many proposals are made, e.g., efforts towards an increase in sustainability literacy and culture in companies and citizens, waste-management programs, waste-recycling systems and concepts, transitioning educational curricula, steering end-users to more sustainable behaviors and designing new product–service systems that keep materials flows at their highest level of utility and value [6]. Therefore, if, on the one hand, design can be considered responsible for the emergence of unsustainable production-consumption practices [31], on the other hand, designers might help to facilitate this sustainable transition. However, are designers ready for this new challenge?

Educating young designers to know and meaningfully use circular strategies is a fundamental first step. Andrews et al. explored the role of education and concluded: “Designers must now respond to very different social, economic and environmental needs

and adopt a holistic approach to problem-solving; they must change their design thinking and practice and lead the development of the Circular Economy by creating products and services that match all inherent criteria of this model. A thorough knowledge of this model must therefore be embedded in design courses so that it can be implemented by all graduates in the immediate future." [32] (p. 313). In order to add to this, Oyelola et al. confirmed the impact of design education on teaching the future designers to promote more sustainable consumer behavior [33], education that can be articulated into nine key circular design competencies of which one is "Circular Materials and Manufacturing", which "is the ability to select and use materials and manufacturing methods for a product to minimize the impact (environment, health, social) while taking into account the full lifecycle of the product and its recovery" [34] (p. 12).

By looking at the DIY, bio-based and circular materials, Barati et al. stated that designers could play an important role in their development and application. In their paper, they propose a framework to identify and articulate the contribution of design to materials development in relation to both the final application and the new material affordances that are perceived, invented and exploited throughout the process of tinkering and making. The researchers posit that emerging design practices at the intersection of design, materials science, biology, arts and crafts have radically changed the role of the designer from a "passive recipient" to an "active maker" of materials [23,35,36]. Pedgley et al. provided recommendations on restoring the existing imbalance in materials and design education by transitioning from a culture of "imparting knowledge about materials" to a culture of "generating experience with materials" [37].

Regarding the active involvement of designers in creatively exploring new material developments, whether or not in collaboration with material scientists or experts, there is a particular domain called Growing Design, which is a combined practice of growing living organisms (i.e., fungi and bacteria) and material (driven) design (MDD) [26,36,37]. There is one specific quote from an article by Camere et al., "By engaging with Growing Design and being in lab environments, designers also establish an open-minded approach toward emerging technologies . . . ", that expresses and ultimately asserts the clear need for the construction of a "bio-makerspace" environment in today's design workspaces in order to provide the designers with the appropriate machinery, tools and equipment to engage with those upcoming emergent bio-based materials [26] (p. 578). Finally, the pathway through which designers explore these new materials can become a point of interest on its own [38]. In the next paragraph, we show how design education proceeds through practice and introduce the idea of the "bio-makerspace".

2.3. The Design Workspace and the "Bio-Makerspace" at UGent Campus Kortrijk

In design education, teaching *through doing*, hands-on approaches and the exposure of students to non-academic actors are very common practices that date back to the Bauhaus School of Design in the early 1900s [39]. Those constructivist and experiential learning approaches fall under the overarching term "Problem- and Project-Based Learning (PPBL)" and are often deployed to educate students—not only designers—on sustainability. The learning process shifts from passive (where the teacher delivers and the students receive) to active (multidisciplinary teams of students working on real-world cases, with the educator acting as coach) [40].

In this context, design workspaces become the arena of this hands-on way of learning. Design workspaces are, in fact, the place where students engage with the tangible process of prototyping their ideas and testing them, an iterative process through which students gain an actionable understanding of complex situations. These are usually designed to allow prototyping with traditional materials: plastics, wood, metals and textiles. Brandt et al. studied the dynamics in current design workspaces and how particular features enable experiential learning, going beyond the traditional classroom environment. As a result, the framework proposed describes three essential elements to understand the design workspace: first, the surface structures, which refers, for example, to the workspace itself,

materials and equipment; second, the pedagogical activities, including iterative design cycles, lectures and feedback moments; third, the nature of knowing and how knowledge is created in the workspace [41]. These essential elements provoke potential cross-pollination between researchers, students and academics by working amongst each other on different and diverse projects in this physical design workspace. Chiu et al. found that one of the main sources of design knowledge for students is peer design students they meet in the design workspace [42]. This aspect is also expressed by a recent study that observed collaboration between student groups working in the workspace on an assignment. They researched the correlation between the systems archetypes used by the students and the number of collaborations the student teams formed amongst each other and with external stakeholders [43,44].

A known example of a workspace structure is the principle of “fablabs” organized through the global network called the “Fab Foundation”. A “fablab” is defined as a technical prototyping platform for innovation, invention, providing stimulus for local entrepreneurship, learning and educating. The Fab Foundation provides all the necessary information in order to be able to set up a fablab, from lab equipment to software packages, to communities, to funding and to lab examples. Some key takeaways of setting up a fablab can be used to set up a design workspace [41,45–47].

In order to make designers experiment with more sustainable materials and applications, they have to be provided with the right environment in which they are able to explore and experiment [23]. In this respect, Yao et al. presented a case study (at the University of California, Davis, CA, USA) where the researchers launched and maintained a so-called academic “bio-makerspace”. In their article, they shared their lessons learned from creating, operating and sustaining such a lab, including machines, tools, equipment and their costs and lab importance. They additionally reported in their three-year study that design students were have supported in this “bio-makerspace” [48]. Although this research took place in a more biomedical engineering-minded (BME) context, it is a good example of a bio-makerspace in a more interdisciplinary design engineering study area in an academic environment. Furthermore, another study published their insights on how sustainability is constituted in the fablab ideology, and the researchers found that involving a range of stakeholders with technical and/or environmental expertise will raise the visibility of sustainability-oriented priorities [49]. In addition, it is essential to extrapolate and extend sustainability-oriented priorities throughout the whole academic culture, infrastructure, staff and stakeholders. In this respect, two recent studies demonstrate the importance of introducing a more sustainable, circular culture regarding material usage in the School of Design. In particular, it concerns the disposal and triage stage of leftover/wasted materials, but also the reuse of some of them afterward. Both papers aimed to measure the impact of a redesigned waste recycling station and the impact of the introduction of a material exchange program, and the article by Manfredi et al. described the circular design workspace as a local internal circular economy [50,51].

From the literature above, it is now hypothesized that replacing the conventional prototyping materials of industrial design students with bio-based circular materials, which, for example, students should make or grow themselves, will alter the prototyping process of the students to a more circular one. Specific surface structures, pedagogical activities and a specific epistemology might contribute to facilitating the growing and making of materials. This surface structure, including the pedagogical activities and epistemology, we call a “bio-makerspace”. From the aforementioned literature, it is hypothesized that implementing a bio-makerspace might create circular skills, and these skills could be useful in the future career of the students. All of this might support skewing the future reality to a more circular economy. This substantiates the decision to expand the design workspace of Ghent University’s Campus Kortrijk to include specific technologies for circular, bio-based and biodegradable materials as a means of experiential learning.

Therefore, in this study, we want to research what the most important elements to set up a “bio-makerspace” in an academic design workspace are. What happens when

design students use such a “bio-makerspace”? What do they experience as main barriers and enablers? In this paper, a case study of setting up such bio-makerspace is described. A student group tested the proposed “bio-makerspace” with a project-based assignment given within a course. Their experience with using this new space is qualitatively analyzed and reported in the next sections, concluding in a list of the most essential elements of a “bio-makerspace” in the academic design workspace, accompanied by an evidence-based thorough discussion of their barriers and enablers. In our intention, these results might support other academic institutions to also introduce such “bio-makerspace” in their design workspace.

3. Method

3.1. Context

In 2020, Ghent University published a sustainability report that includes the university-wide vision on sustainability issues highlighting the strong focus on multi- and transdisciplinary approaches to these challenges, considered wicked and ever-evolving. The report also shares the actions that are taken and guidelines to approach several topics as the implementation of sustainability in education and research, sustainable campus development, energy use, mobility and others [52]. The study presented here was developed at Campus Kortrijk (a detached campus of the university) and specifically at the Industrial Design Center where industrial design engineers are trained, spending most of their time in the previously mentioned “design workspace”. In this education, several actions are taken to increase the sustainability literacy of students, actions grouped in the so-called “Design for Sustainability learning line”. The action this article focuses on is specifically aimed at informing students around the topic of the emerging DIY, circular and bio-based materials by setting up the “bio-makerspace” previously mentioned. The “bio-makerspace” implemented tangible infrastructures found in the workspace as well as pedagogical activities, such as a set of lessons (theory, tools and methods) to Design for Circularity and specifically with DIY circular and bio-based materials. By looking at the tangible infrastructures, in the “bio-makerspace”, we can find a fridge, a sink, a ceramics 3D-printer, a laminar flow cabin, an incubator, an autoclave, some molds, a (hydraulic) press and other smaller tools such as mixing bowls, casseroles and pans, kitchen utensils and others. All these machines were initially selected in order to assure the possibility to prototype and design with several commonly known recipes of DIY bio-materials starting from different input waste materials (e.g., woodchips, natural fibers, kombucha, eggshells, fruit and vegetable waste, coffee grounds, knotweed clippings, mycelium). The “bio-makerspace” is displayed in Figure 2.

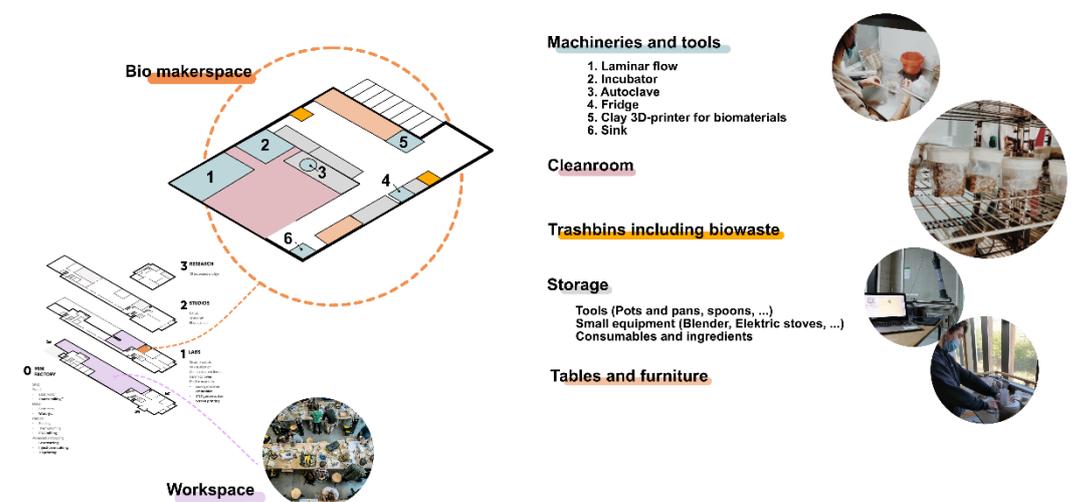


Figure 2. Sitemap of the current “bio-makerspace” in the design workspace at Ghent University (Belgium), Campus Kortrijk, Industrial Design Center [53]. Figure adapted by the authors.

3.2. Study Set-Up

The overall methodology follows a qualitative “Research through Design” (RtD) approach that consists in the observation of the development process of an artifact, a process which becomes itself the knowledge-generating one [54]. Specifically, the study reported here was conducted during the course “Designing in a cybernetic and System-Oriented Way”. Over the course of 12 weeks, the 3rd year students were trained in systems-thinking, complexity, cybernetics and system-oriented design by following 2-h weekly lectures and had 4 h per week access to the lab to work on a steered assignment (divided into 15 teams of 3 to 4 students). The assignment aimed to implement, in a self-sustaining way, the DIY bio-based materials in their own education as an alternative for the toxic technical-streamed prototyping materials, each team working with a specific material or technology present in the new “bio-makerspace”. The main goal was to develop a system that would enable other students too to learn and work with the new material or technology. For this purpose, students were asked to conduct an iterative process of observation–decision–test typical of the cybernetic approach [55]. In short, students worked with the material given (for example, learn to 3D-print an egg-shell-based material) (Table 1) and implemented a system for this material to be used by other fellow students (for example, digital tutorials, but also contact with local bakeries to gather the eggshells).

Table 1. An example of a challenge; team 3D-printing eggshells.

What	Explanation
The challenge	Clay 3D printers open up new opportunities for printing with new bio-based materials. How can a self-sustaining system be set up to engage stakeholders and actors to use the Stone Flower printer at IDC? How should the material be made, conserved and discarded?
Recipe	Materiom, eggshell paste for 3D-printing https://materiom.org/recipe/601 (accessed on 9 February 2021)
Input materials	Eggshells, Alginate, Xanthan
Outcome: Understanding the process	
Outcome: Making instruction videos	
Outcome: Giving workshops to fellow students	

During the study, each team was asked to post each week 3 highlights of their progress (stored and visible here: <https://www.prototypingcirculair.com/>, accessed on 17 August 2021) [56]. The highlights reported on this website are our main data source and contain (1) images and (2) (not always) text (Figure 3).

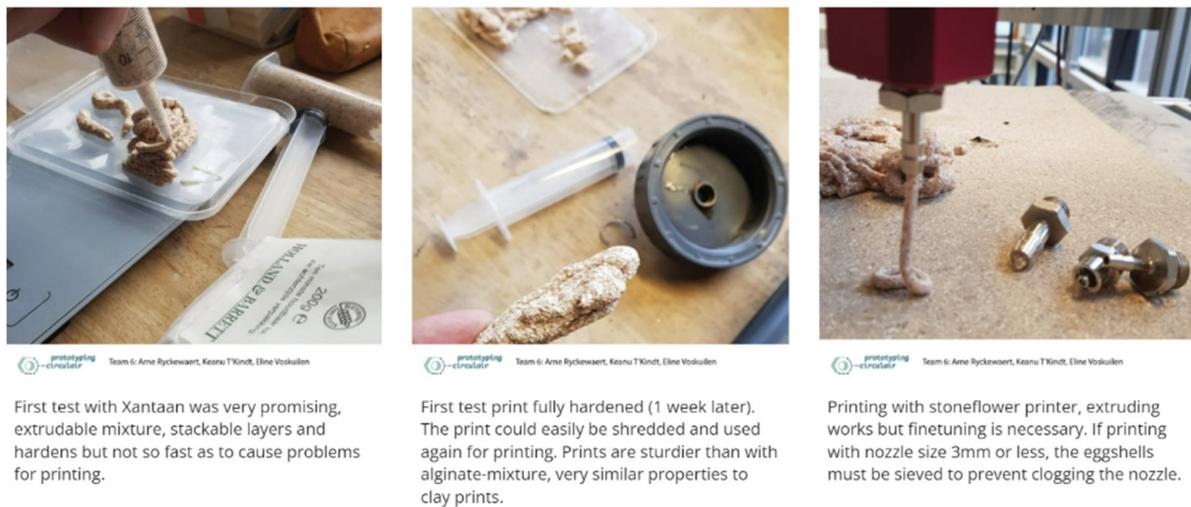


Figure 3. Example of three reported highlights of the team working on “3D-printing eggshells”. Photos and text by the students Arne Ryckewaert, Keanu T’Kindt and Eline Voskuilen of the team “3D-printing eggshells”.

3.3. Data Analysis

At the end of the semester, all the weekly highlights provided by the students (=402 data units) were collected and analyzed. Specifically, for the qualitative data analysis the lead researcher followed the Grounded Theory approach, allowing codes to arise from the data without the use of external theories or frameworks [57]. More specifically, the Quagol methodology was followed in order to capture the rich insights of qualitative data, and the software Nvivo practically supported this task [58]. Following the Quagol methodology, researchers were able to familiarize themselves with the collected data in a spontaneous manner, identifying 5 overarching codes that help to answer the initial research question of what it takes to set up a “bio-makerspace” in contemporary design workspaces (Table 2). Furthermore, all emerged insights were cross-analyzed through the question “What barriers and enablers are encountered by the students”?

Table 2. The 5 initially identified codes, for which subcodes emerge during the qualitative data analysis.

Code	Explanation
Input material	What materials are used by the teams during their entire project?
Knowledge transfer to design workspace	What resources/channels/methodologies are used by the teams in order to disseminate their acquired knowledge?
Manufacturing processes	What manufacturing processes are applied by the teams in their project?
Methodologies	What methodologies support the students’ processes and findings?
Tools and machines	What machines, tools and equipment are used by the teams?

From this point onwards, one researcher transcribed the 402 highlights (data units) of the 15 teams following 2 steps, (1) literally describing what can be seen in the highlight-image itself and (2) translating (if necessary) the written highlights text to English. At this point, the more detailed data analysis and coding took place, generating subcodes. Then,

queries were created to filter, organize and cross-analyze the generated subcodes. In this respect, queries were analyzed on different levels of detail in the data.

1. The number of teams that referred to a specific subcode is listed. This figure gives us *the overall recurrence of a specific subcode*;
2. A *threshold table* is provided, where the threshold for subcode inclusion is arbitrarily chosen to be the average of the team referrals per code (e.g., for code “input material”, the average amount of teams that referred to the identified subcodes was 1.86. Therefore, the subcodes only referred to by >1.86 teams are included in the table). This figure gives us an overview of the most recurrent subcodes per code;
3. A *cross-coding-analysis* is created between the most recurrent subcodes and the question of whether these represented barriers or enablers for the students. This table is a gradient highlighting the subcodes with the most barriers and enablers.
 - a. Finally, a *narrative discussion* of the most recurrent barriers and enablers is also reported in the “Results” section.

4. Results

The results from the qualitative data analysis of the students’ highlights (=402 data units) while working with the new “bio-makerspace” are thoroughly reported on three different layers of detail.

4.1. The Emerged Subcodes

As described in the method section, the first result of this study is the subcodes that emerged from the qualitative data analysis of the highlights dataset of 402 data units. In total, 106 subcodes emerged from this analysis. In Table 3, they are all summarized to their respective identified code. In this table, for the sake of simplicity, the researchers did not include the number of teams that referred to each of the subcodes. Nevertheless, this data is available and can be obtained by anyone interested by contacting the authors.

Table 3. Summary of the 106 subcodes that emerged for each identified code during the qualitative data analysis.

Codes	Subcodes
Input material	Agar-agar; Alginate; Avocado pit; Baking powder; Cardboard; Casein; Chalk sticks leftovers; Coffee ground; eggshells; Ethyl alcohol; Fruit and vegetables; Gelatin; Glycerol; Grass clippings; Hemp; Hide glue; Japanese knotweed clippings; Metal; Milk; Mussel shells; Mycelium (spores and substrate); Ox tongue root; PLA; Red beet; SCOBY; Scrap paper; Starch; Sugar; Tap water; Tea; Vinegar; Waste water; Water; Wax; Whey; Wood; Wood chips; Xanthan
Knowledge transfer to design workspace	Creating a resource map; DIY-kits; Educational curriculum change; Instagram; Instructable; Instruction manual; Posters; QR-codes; Sample board material wall; Shared spreadsheet; Video tutorial; Website; Workshops; YouTube channel
Manufacturing processes	3D-Printing; Boiling; Curing; Dehumidifying; Demolding; Drying; Dyeing; Filament extruding; Gluing; Grinding; Growing; Laser cutting; Molding; Pressing; Shredding; Sieving; Sterilizing; Welding
Methodologies	Behavior over time (BOT) graph; Black box diagram; Case collaborations; External stakeholder collaboration; Life cycle analysis-assessment (LCA); Prototyping iterative and evolutionary; Systems thinking; Validating the material; Wicked problems
Tools and machines	3D-print filament extruder; Autoclave; CAD-CAM software; Casserole; Ceramics 3D-printer; CES Edupack database; Dehumidifiers; Drying rack; Filter-straining cloth; Fridge; Furnace; Heavy metal grid; Incubator; Jars; Laser cutter; Measuring cup; Microwave oven; Mold; Mycelium growing bags; Oven; Pinterest; Plastic foil; Press; Shredder-blender; Sieve; Spoon; Syringe; Water paint pencil; Wood framing

4.2. Most Recurrent Subcodes

Table 4 (column 1, # Teams) derives from Table 3 and excludes the subcodes referred less than average (65 of the 106 subcodes were excluded as not mentioned above average). The remaining codes are color-graded from white to more saturated blue, meaning to

highlight the most recurrent subcodes from the remaining others. As such, this emphasizes the most frequent subcodes of the ones still included.

Table 4. Summary of the 41 remaining subcodes that recurred the most in the 15 teams, accompanied by the number of coded barriers and enablers that emerged from the cross-coded query analysis.

Codes	Subcodes	# Teams	# Barriers	# Enablers
Input material Threshold > Avg (1.86)	Agar-agar	3	0	5
	Alginate	2	0	1
	Cardboard	2	0	0
	Casein	2	1	0
	Coffee ground	4	1	2
	Fruit and vegetables	2	0	1
	Gelatin	4	0	0
	Glycerol	4	0	2
	Japanese knotweed clippings	2	0	0
	Mycelium (spores and substrate)	6	4	5
	Starch	2	0	1
	Vinegar	2	0	1
	Water	6	1	4
	Wax	2	1	2
	Wood	3	1	2
Wood chips	4	2	3	
Knowledge transfer to design workspace Threshold > Avg (3.92)	Educational curriculum change	4	0	4
	Instruction manual	4	0	0
	Posters	7	1	0
	QR codes	7	1	2
	Video tutorial	7	0	0
	Website	8	1	4
Manufacturing processes Threshold > Avg (2.50)	Workshops	7	0	6
	Boiling	3	0	0
	Drying	10	2	6
	Dyeing	6	4	4
	Growing	3	3	3
	Molding	4	0	2
Methodologies Threshold > Avg (8.55)	Pressing	3	0	2
	Case collaborations	12	4	16
	External stakeholders collaboration	12	4	14
	Prototyping iterative and evolutionary	15	15	31
	Systems thinking	12	0	17
Tools and machines Threshold > Avg (2.10)	Validating the material	15	8	19
	Casserole	3	0	1
	Furnace	4	0	1
	Jars	4	1	3
	Mold	8	2	6
	Oven	6	1	3
	Press	4	0	1
Spoon	3	0	1	

4.3. Most Recurrent Subcodes and Their Barriers and Enablers

Additionally, Table 4 hosts two other data variables, shown in the two columns “number of Barriers” and “number of Enablers”. These contain the results derived from the cross-coded analysis, where the number of barriers and enablers are identified and counted for each most recurrent subcode. Afterward, these data results are also color-graded to highlight for each code the subcodes that accounted for most of the barriers and enablers. In total, 58 barriers and 175 enablers were identified for the most recurrent subcodes. An example of a data transcription that was identified as a “barrier” for the manufacturing process of “drying”:

“We washed some avocado seeds and let them dry for a week. A lot of them dried nicely and gave us useable material, but some still developed mold, especially on the bottom of the seed. Probably because this side was on the paper towel, which causes it to lose a lot of ventilation #mold #Bio #ventilation.”

The enablers and barriers of the most recurrent subcodes were further analyzed, grouped and described in the next paragraphs.

4.4. Common Barriers

By observing those pain points that illuminate from the barriers of each subcode, we summarized the following main findings, each accompanied by one example quote and figure from the weekly highlights dataset.

(1) Regarding the **“input materials”**, some new processes were hard to grasp and led to outcomes not matching the expectations of the students. Some students were more concrete in describing the expectations of the material that were not met; insufficient strength, shrinking of the material and the creation of mold on the material (e.g., the waste substrates used in growing materials are sometimes contaminated and hard to be maintained sterile) (Figure 4). Additionally, for the creation of some bio-based materials, suppliers play an important role and must be accounted for (e.g., mycelium spores/starter took time to be gathered by students).

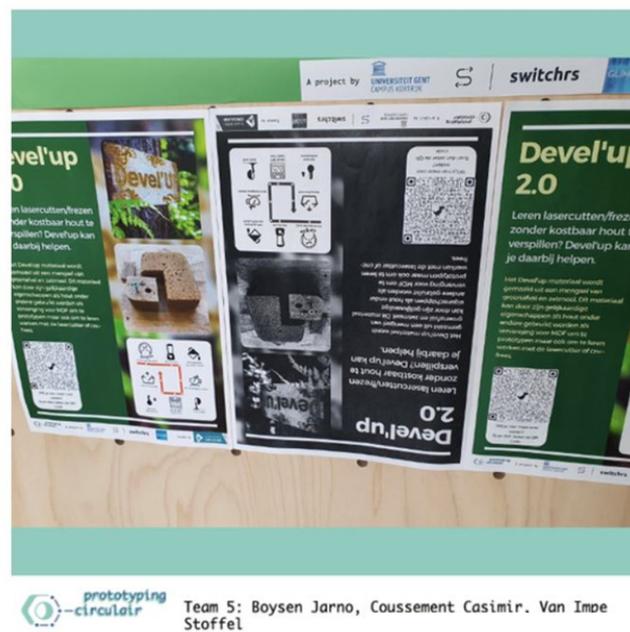


“We noticed that some of our tests when making the material still fail from time to time. (...)”

Figure 4. Example of students describing a failed prototype, photo and quoted text by the students; Jarno Boysen, Casimir Coussement and Stoffel Van Impe of the team “Devel-UP2.0”.

(2) Regarding the **“knowledge transfer”**, students mentioned the difficulty of reaching and engaging fellow students as much as they wished regarding website views or QR-scans of posters (Figure 5).

(3) Regarding the **“manufacturing processes”**, there is one particular barrier that stands out the most in many teams, which is the formation of molds on bio-based materials (Figure 6). Students had mixed results when trying to control the formation of mold by drying the material, trying to work more sterile, using distilled water and using air-ventilated molding tools. Students reported on finding ways to shape the material, the creation of a good mold (tool) was mentioned a few times as important. Furthermore, participants mentioned that the growing and drying of materials takes time (weeks); this time has to be taken into account in the creation of a biomaterial.



"We are monitoring the traffic generated to our website page and so far we don't have a lot of clicks. We need to look for better ways to get people engaged with it."

Figure 5. Example of students sharing their experience and knowledge through posters and QR-codes. Photo and quoted text by the students; Jarno Boysen, Casimir Coussement and Stoffel Van Impe of the team "Devel-UP2.0".



"After making the samples last week, we tried drying them, to avoid mold, by using an oven. Sadly, this didn't make much difference, the sample still formed mold. We tried blending the samples and some new sawdust to make smaller sawdust."

Figure 6. Example of students experiencing difficulties due to unwanted mold formation. Photo and quoted text by the students; Leander Bossuyt, Toon Nachtergaele and Lowie Vermaete of the team "Wood chips".

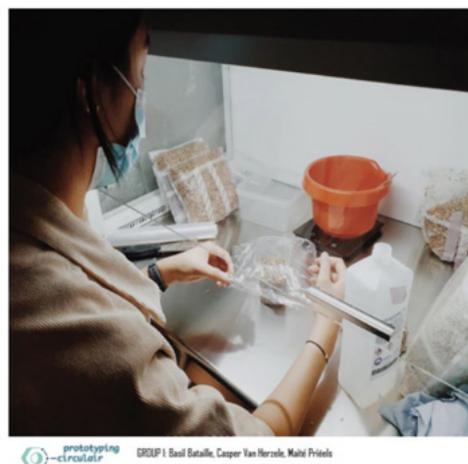
(4) Concerning the "methodologies" that supported the students in their projects, it seems that the results of a case collaboration depend on the results of each team's contribution [43] (Figure 7). Furthermore, most barriers in this code occurred in the process of prototyping iterative and evolutionary, where frustration was the main pain point in working with these types of material. This is also the case in the process of validating a material iteration, where the material often fails to deliver the desired results.



"Last week we saw the results of our collaboration with Group 9. This was not a success as shown in this picture. We had hoped that group 9 could provide a bio-mold for the growth of mycelium. Unfortunately, this did not produce favorable results, so we will continue our search for a bio mold. We did have an inkling that this was not such a good idea since the bio-mold consists of coffee and gelatin and coffee is also used as a fiber on which the mycelium can grow. We learned a lot from this collaboration."

Figure 7. Example of students experiencing problems related to cross-team collaborations as part of their learning-through-doing process. Photo and quoted text by the students; Casper Van Herzele, Maité Priëls and Basil Bataille of the team "Mycelium".

(5) Regarding the **"tools and machines"**, Some participants felt that a learning curve of using the machines and tools caused failed samples. Shaping the samples and the search for the right mold was mentioned as challenging; one student team questioned the sustainability of these molds that are used in this process (e.g., thrown away plastic wraps for mycelium growth) (Figure 8). Furthermore, as mentioned above, the formation of mold on the materials formed a problem, not only when creating the material but also when storing the materials in closed jars or containers, even after using an oven to dry out and sterilize the materials, mold can still develop.



"(...) Since we had already made the hemp sterile in week 2, we could immediately move on to mixing the hemp with the mycelium. These were then placed in a mold and covered with foil. One remark is that the mold is made of plastic and is therefore not durable. We will look for a solution to make the whole mycelium process as sustainable as possible."

Figure 8. Example of students questioning the sustainability of their utensils. Photo and quoted text by the students; Casper Van Herzele, Maité Priëls and Basil Bataille of the team "Mycelium".

4.5. Common Enablers

For each code, also the most important enablers were identified, each also accompanied by one example quote and figure from the weekly highlights' dataset.

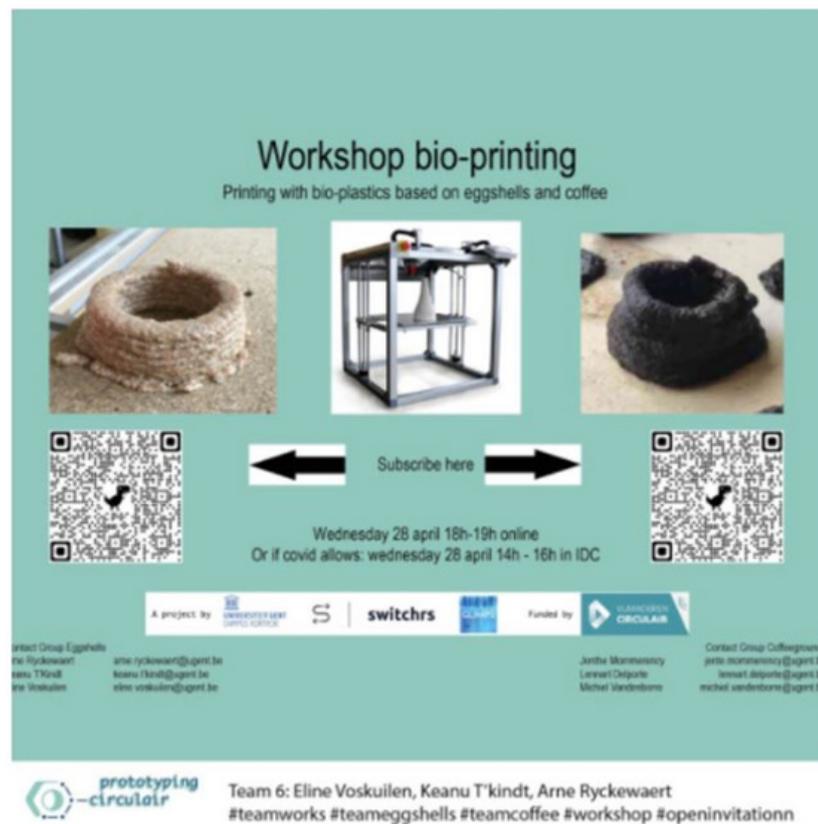
(1) Regarding the “**input materials**”, some binders proved to be very well performing and easy to use (e.g., agar-agar, glycerol and starch) (Figure 9). Students described promising tests of the materials; fire-resistant, slight flex, relatively strong and does not break apart easily. Additionally, some materials delivered a wide range of possibilities, stimulating the students into further experimentation (e.g., mycelium-based materials were grown, pressed and baked under very different conditions). Widely and instantly available waste materials in the atelier (e.g., wooden chips) were of great support for students' creative experimentation. Some students mentioned the ability to reuse the prototypes as input ingredients for a second iteration. Finally, water was fundamental for almost all bio-based materials. Therefore, a “bio workspace” without direct access to water would not be suitable.



“We experimented with agar agar as a binder. This turned out to be quite promising, but we need to figure out how to apply more pressure. We also tested this with different sizes of fi-bers.”

Figure 9. Example of students having some great success in their experiments with agar-agar binder material. Photo and quoted text by the students; Jamie Catry, Milan Claeys and Gijs Habets of the team “Natural fibers”.

(2) Regarding the “**knowledge transfer**”, contents implemented in the course triggered the first knowledge on different bio-based materials. In addition, online platforms helped students to re-organize and spread their knowledge (e.g., video’s, slideshows, pictures, digital instruction manuals) were uploaded on the website prototypingcircular.com (accessed on 17 August 2021); while the Instagram page “Prototyping Circulair” hosted more short videos of experiments or display of certain properties [56]. As previously mentioned in the barriers section, reaching and engaging fellow students by using QR codes did not reach expectations; QR codes provide good feedback on the number of scans, providing the students with a good grasp on how much their contents were accessed. Other ways to spread knowledge were the organization of workshops to fellow students, a very hands-on approach that lowered barriers to participation (Figure 10). As this course took place during the COVID-19 pandemic, a limitation on the number of participants was anyhow necessary.



“The second highlight is our open invitation for our workshop. This will be taking place the 28th of April, on campus and corona proof. We choose to do this on campus to ensure the most fun and informative experience.”

Figure 10. Example of students organizing a workshop to lower the barrier to teach the creation of their bio-printable material. Photo and quoted text by the students; Lennart Delpoort, Jenthe Mommerency and Michiel Vandenborre of the team “Bio-plastics”.

(3) Concerning the “**manufacturing processes**”, we could state that many seemingly limitations of these bio-based and circular materials had the advantage of triggering creativity by allowing students to experiment with a trial-and-error approach (Figure 11). For example, dyeing with natural color agents was reported to be tricky—due to the inconsistent and temporary results—yet capable of delivering very surprising outcomes. The growing capacity of materials asked for a shift in students’ approach that had to consider more variables affecting the process than previously. Finally, compression molding emerged as the most used way to shape these materials, which is easy to be executed in the workspace and allows the rise of certain materials’ properties.

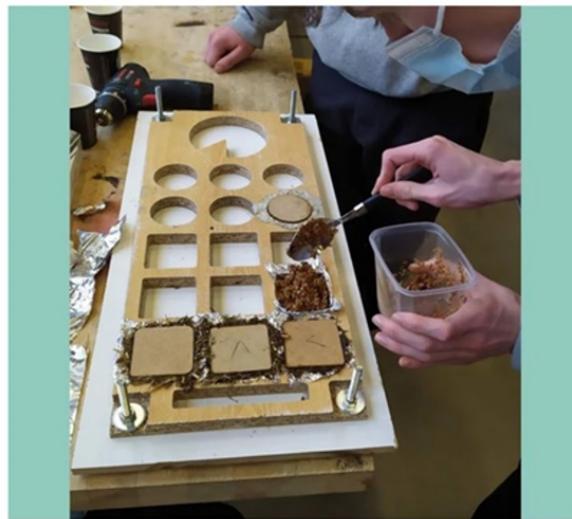
(4) Considering the used “**methodologies**”, it is found that collaborations among teams fostered cross-pollination of ideas (Figure 12). Furthermore, collaborations with external non-academic stakeholders prove to be of significant importance (i.e., in supporting the teams and providing them with the necessary knowledge and resources). These collaborations additionally created the opportunity to share the projects with a wider audience beyond the walls of the design workspace. Another significant methodology that supported the students’ knowledge creation was the iterative prototyping process, which was adopted to optimize the obtained results continuously. Finally, a wider systemic view helped the students in taking more informed actions (e.g., new materials were often seen in a dynamic wider context in which parts are interconnected).



prototyping
circular Team 2: Deprez Emile, Mussche Wout, Hocheplid Amber

“This week, we finally got the result from our first batches of kombucha leather. We made two setups to dry the sheets: one on a wooden board and the other suspended between a framework. The results showed that the framework gives a better result.”

Figure 11. Example of students making progress by trial-and-error experimentation with different manufacturing processes. Photo and quoted text by the students; Emile Deprez, Amber Hocheplid and Wout Musshe of the team “Kombucha”.



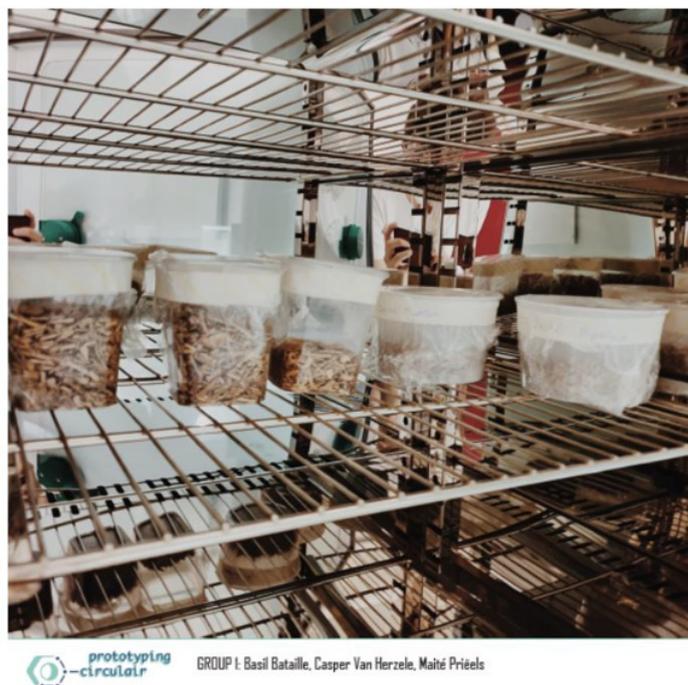
prototyping
circular Team 12: Leander Bossuyt, Toon Nachtergaele, Lowie Vermaete

“We teamed up with group 11 (molding) to try out their mold perforated with holes. We also talked with the mycelium group and the bio-coloring group to further develop our options.”

Figure 12. Example of students laying connections with other teams to increase their innovations collaboratively. Photo and quoted text by the students; Leander Bossuyt, Toon Nachtergaele and Lowie Vermaete of the team “Wood chips”.

(5) Finally, concerning the **“tools and machines”** that are mostly used in the “bio-makerspace”. Casseroles were found to enable mixing the different constituents and preparing the bio-based material recipes. A furnace eventually provides the necessary heat for the creation of some bio-based material recipes. Containers and jars are identified to provide the opportunity to store, cure and grow bio-based materials (Figure 13). Molds provide a way to steer the shape of bio-based materials in the desired direction. An

oven serves as a way to dry, sterilize and cure bio-based materials. A press presents the opportunity to compress bio-based materials to make them denser but also provides a way to squeeze out the remaining moisture from the materials. Eventually, a spoon and other kitchen utensils are elementary to create bio-based materials.



prototyping
-circulair GROUP 1: Basil Bataille, Casper Van Herzele, Maité Priëls

“After mixing and transferring to the mold, we placed the jars in the incubator, which has a constant temperature of ± 26 °C (± 299 K). This is the optimal growth temperature for the mycelium. By the end of week 4 and the beginning of week 5 we should already see results. Exciting!!!”

Figure 13. Example of students using jars and containers to control the growth environment. Photo and quoted text by the students; Casper Van Herzele, Maité Priëls and Basil Bataille of the team “Mycelium”.

5. Discussion

Researchers, academic staff, teachers and design workspace responsables could use the codes that emerged (Table 2) as guiding categories to set up a bio-makerspace.

The first category, the methodologies, could be interpreted as the course knowledge that is provided. In this study, the methodologies that appeared are connected to cybernetics as this is the theoretical background the students had during the project. Turning this around, defining which methodologies are needed to enable working with the bio-makerspace opens up another, yet to be researched, interesting scope.

The second category is the knowledge transfer in the design workspace, to define what will be the main tool to provide the creation of knowledge within the workspace. In this case study, defining the way that knowledge transfer is achieved was part of the assignment for the students, resulting in a multitude of possible tools. On a personal note, we would suggest using a very selected set of tools to provide knowledge transfer, resulting in centralized and structured knowledge transfer.

The third category is a combination of the tools and machines, the manufacturing processes and the input materials. Defining which recipes to choose has a big impact on which machines and processes are needed and thus which input materials need to be bought or salvaged. Table 3 and the color grading in Table 4 can provide a guide in selecting which input materials, machines and manufacturing processes cover a broad range of possibilities.

To set up a “bio-makerspace” there is a need to find a fitted space to provide tools and machines. We found out that ours was too small, definitely in COVID-19 times, resulting in students moving machines and tools to the main workspace. Looking at the category “manufacturing processes” can broaden up the potential look on the needed machines. For example, since an oven is installed in the lab, which resulted in the manufacturing process “drying”, other tools and equipment than an oven can be bought and installed to achieve the same function.

One of the most mentioned barriers on the input materials was the development of mold on materials, while the advantage of using these bio-based materials is that they are easy to compost, shortening the lifespan as described in the introduction. This advantage comes with the barrier of sometimes degrading too soon, for example, when the product is still in use, asking for extra care to control this process. Looking at these dynamics, we see what we interpreted as a value, environmentally speaking, can as well become a barrier for the students or even be experienced as an intrinsic imperfection of the material. In addition, being new materials, students have certain expectations on how these materials would look and behave, expectations that are not always met, with either positive or negative effects. This opens up a reflection on the need to explore new identities, values and user experiences for the DIY bio-based and circular materials.

Limitations

In this paper, the core elements needed to set up a “bio-makerspace” as well as the resulting systemic interactions were identified. Nevertheless, there are some limitations to this study that should be acknowledged. Firstly, when looking at the fifteen different teams, there was some overlap of input material. As such, the most recurrent subcodes of the input materials could be skewed towards these overlapping ingredients. Another limitation, but also unbiased strength, of this study was the fact that the students were only asked to report on their progress and not on encountered barriers or enablers. The students were aware that this project would be graded, which means they could be biased to report more on good results than on bad ones. This might also explain the fact that this study could identify more enablers (175) than barriers (58). Furthermore, the impact of installing a new “bio-makerspace” in an academic design workspace, based on the knowledge acquired through this study, was not yet measured. In particular, the impact on the circular design behavior, literacy and culture of the students by installing this “bio-makerspace” in the design workspace was not studied, measured or analyzed.

6. Conclusions

In conclusion, as there is often an “over-dimensioning” between the material lifespan and its application, importance is given to bio-based materials. In pursuit of those more sustainable materials, the important role designers play is acknowledged, along with the material scientists and other experts. In this respect, UGent Campus Kortrijk decided to implement a “bio-makerspace” in the design workspace. Specifically, this article aims at capturing and analyzing data from a 12-week study in order to learn what it takes to implement this “bio-makerspace” in terms of use dynamics and barriers and enablers for its successful use. From the qualitative analysis of coding 402 data units (including figures and text) delivered by 45 students, Table 4 was designed. This table displays the identified most essential elements of a “bio-makerspace”, possibly inspiring and informing other researchers and teachers who might also want to implement a “bio-makerspace” in their own campuses. The article ends with discussing the barriers and enablers that emerged by analyzing the students’ perspectives.

As a future perspective, it is our intention to follow the development of the “bio-makerspace” and to explore how the implementation of a “bio-makerspace” might create circular skills, supporting the education of more future-proof designers. In general, it is certainly worthwhile to look at the real impact (environmental, societal, and even economic) of implementing such a “bio-makerspace” in a design atelier. Furthermore, we aim at

also learning from professionals, outside academia, who already use these materials. As other research lines have already been explored, we believe that acknowledging the new identity of these new materials can have a fundamental role in transitioning to a more circular future.

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Abbreviations

The following abbreviations are used in this manuscript:

D4S	Design for Sustainability
RtD	Research through Design
PPBL	Problem- and Project-Based Learning
CE	Circular Economy
DIY	Do-It-Yourself

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