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Introducing Feedstock-Material-Product Combinations: Revaluing Wastewater Into Bio-composite Materials And Meaningful Applications

Marita Sauerwein[a,b], Peter R. Mooij[a,b], Stephen J. Picken[b], Mark C. M. van Loosdrecht[b]
a) AMS Institute, Amsterdam, The Netherlands
b) Delft University of Technology, Delft, The Netherlands

Keywords: Biobased feedstock; Biobased and wastebased materials; Circular economy; Product design; Bio-composite.

Abstract: The reuse of waste streams is one of the key principles of a circular economy. Wastewater is a significant waste stream in urban regions, yet largely unexplored for material and product development. We therefore developed a bio-composite using wastewater as feedstock. Consequently, this bio-composite relies on sustainable resources and is biodegradable. As such it is a relevant material for a circular economy. However, a material only becomes of value when suitable applications and end of life options are found. The feedstock, material and product level all influence each other and hence we propose to iteratively consider them during development. The goal of this paper is therefore twofold; we introduce *Feedstock – Material – Product combination* (FMP-combination) to approach renewable material development in a circular economy, and we introduce Re-plex, as a result of value appreciation of wastewater and example of an FMP-combination. With the development of Re-plex, we prove the value recovery of a major organic waste stream. Due to the iterative process between feedstock, material and product level, we could extend the lifetime of an organic waste stream into a high value material for which interesting applications were found with market parties, i.e. façade panels for the building industry and 3D structures for nature restoration in aquatic settings. From this we conclude that approaching the development of a biobased material for a circular economy as an FMP-combinations places the material in a broader context. This helps to steer the optimization process as it gives insight into which properties are required to meet the envisioned product lifetime and high value recovery.

Introduction

The reuse of waste streams is one of the key principles of a circular economy (MacArthur, 2013). Waste streams should therefore be considered when developing materials and products for a circular economy (Velenturf & Purnell, 2021). Wastewater is a significant, yet largely unexplored, waste stream in urban regions for material and product development. Currently, wastewater is used for energy production via production of biogas, but hardly for material and product development. This is a missed opportunity, because products and materials are valued higher in the biomass value pyramid (figure 1) and are therefore preferred over applications lower in the pyramid (Van Der Hoek et al., 2016).

We developed a bio-composite of which the main components originate from wastewater. Composites are valuable materials, because they offer interesting material properties (e.g. strong, stiff, and light weight). A composite consists of fibres (e.g. glass-, carbon-, or natural-fibres) and a resin that binds these fibres together (e.g. epoxy, polyester). However, fossil-based composites are difficult to reuse or recycle (Joustra et al., 2021), and as such have a poor environmental performance in terms of end-of-life strategies. On the other hand, fully biobased composites can

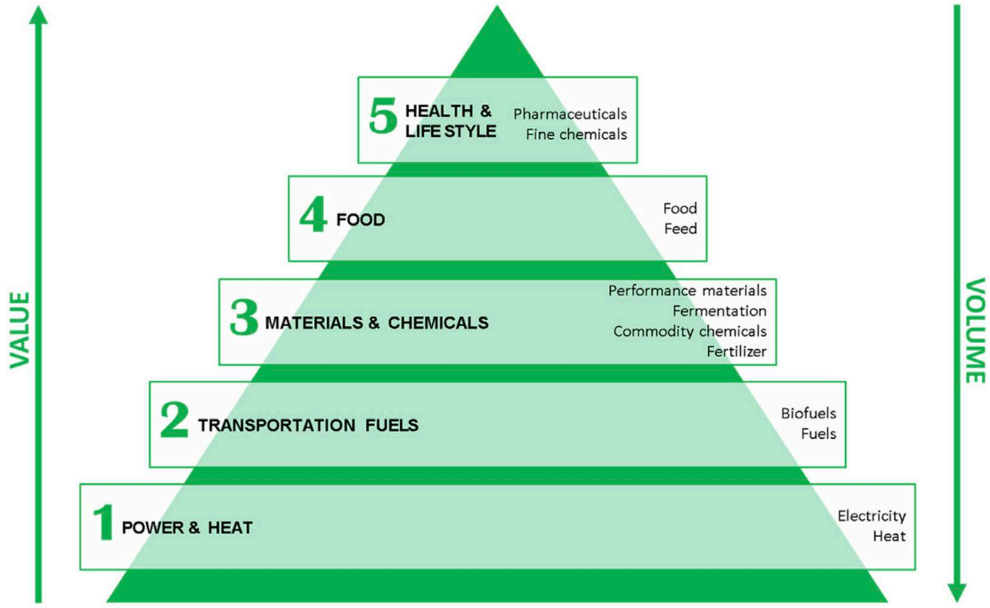

Figure 1. Biomass value pyramid @Van Der Hoek et al., 2016.

biodegrade, hence providing a sustainable end-of-life option; the composite serves as feedstock for (microbial) organisms and re-enters the biological cycle (Bakker & Balkenende, 2021).
The feedstock of our bio-composite relies on sustainable resources and as such is relevant for a circular economy. However, a material really becomes of value when suitable applications are found. Furthermore, in a circular economy materials and products should be preserved at the highest value for as long as possible (Korhonen et al., 2018). Since material development and product design influence each other on end-of-life scenarios, they should be considered together. A product for example can only be recycled when it is made of recyclable materials, but in addition the product should be designed in in such a way that the materials can actually be harvested for recycling.

In other words, when developing biobased materials for a circular economy both feedstock, material and product should be considered. In this paper we therefore propose to approach development in such a way that

Figure 2. Linear relationship between feedstock, material and product level.

feedstock, material and product development strongly interact. The goal of this paper as such is twofold; we introduce *Feedstock – Material – Product combination* (FMP-combination) to approach renewable material development in a circular economy, and we introduce Re-plex, as a result of value appreciation of wastewater and example of an FMP-combination.

FMP-combination

In traditional material development feedstock, material and product have a linear relationship as shown in figure 2. However, in a circular economy, these levels strongly depend on each

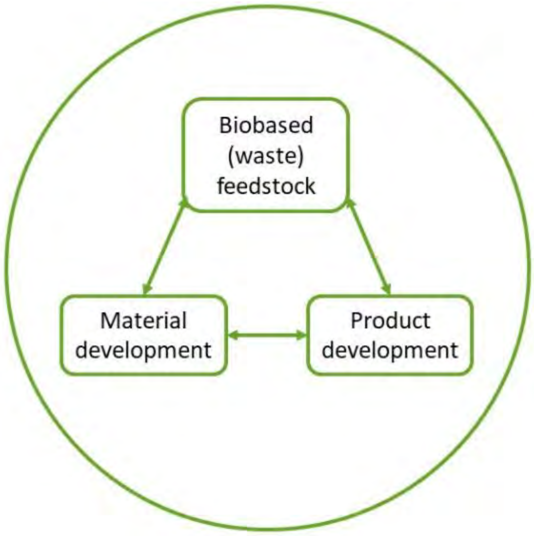

Figure 3. feedstock-material-product combinations (FMP combinations).

other when aiming for high value recovery. We propose to iteratively connect feedstock, material and product, so that all stages can inform each other from early development onwards. Moreover, we should not develop materials and/or products, but approach new development as Feedstock – Material – Product combination (FMP-combinations). Figure 3 graphically represent this interdependency.

Identifying a suitable FMP-combination depends on many factors, e.g. size of the biobased (waste) stream, material characteristics and market interest for possible applications. We therefore propose to move back and forth between the different levels from early development onwards so that all levels inform each other and are closely connected.

Materials and Methods

In this paper we approached the development of Re-plex as an FMP-combination. The focus in the development process thus lays on wastewater as feedstock, a biocomposite as material, and suitable applications as products. In this case, we found two applications, i.e. a nature-restoration structure, and a façade panel. The materials and methods corresponding to feedstock, material and product are described below.

Feedstock level

All components of Re-plex are biobased and the main ingredients, i.e. the fibres and binder, originate from wastewater. For the fibres we opted for cellulose-fibres from retrieved toilet paper. For the resin we used Kaumera Nereda® Gum (in short: Kaumera), a soluble biopolymer produced in the Nereda® wastewater treatment process. In this wastewater treatment process bacteria produce Kaumera while cleaning of the wastewater. (Pronk et al., 2015). Kaumera has many interesting properties, including the ability to bind fibres together (Felz, 2019). The potential Kaumera production at around 5 kg per person per year is significant, as it would constitute about 10 – 20% of total plastics use. All components of Re-plex and their function are shown in table 1.

Component	Role
Kaumera	Binder
Recell	Fibre
Powder from plant source	Filler
Citric acid	Additive for cross-linking[1]
Glycerol	Additive as plasticizer
Tap water	Additive for flow

Table 1. Ingredients of Re-plex.

Material level

On a material level we defined the formulation, production and properties of the material. The exact composition of the components and the production process were found from experimentation and trial-and error optimisation. To gain understanding of the material properties both technical and experimental tests were performed:

- *Technical tests*
  To obtain the tensile strength and modulus of Re-plex a three-point bending test was performed according to ISO 14125 with three samples. Fire resistance was tested by performing a flammability test during which a sample was exposed to a flame for 12 minutes. The biodegradability of Re-plex in water was tested by placing samples in salt, tap and canal water for seven weeks. These samples were observed and measured.
- *Experimental test*
  The Ma2E4 toolkit was performed to obtain an understanding of the experiential characteristics of Re-plex (Camere & Karana, 2018). With this toolkit the material is tested on its performative, sensorial, interpretive, and affective qualities. Thirteen respondents tested the experiential characteristics of Re-plex (female: 9 male: 4; age mean 34; Artistic/design background: 5)

Product level

On a product level we sought for suitable applications and used prototyping and field test to further develop and validate these applications. This was an iterative and creative process for which the first results of material

[1] Crosslinking is a process to form chemical bonds to join two polymer chains together. For Re-plex cross-linking is applied to make the material water-resistant and stronger

properties were used. The results from the technical and experimental studies, as well as material samples, served as an input for brainstorm sessions. Several brainstorm sessions were held with different groups and a variety of participants ranging from backgrounds in building, construction, design, nature restoration, and municipality.

During prototyping samples of the material were made to test certain aspects. These prototypes ranged from simple samples to test the production process to prototypes that reflect the foreseen application. For Re-plex we initially made small beams and flat sheets and concluded with 3D tiles and a full prototype for field testing.

For the field test, the prototypes were placed in the context of the envisioned application, i.e. for nature restoration and façade cladding. Re-plex was tested in several environments based on these applications. During these tests several parameters were monitored based on observation.

Results

The results are depicted on feedstock, material and product level.

Feedstock level

The main result on feedstock level is the need for washing Kaumera. During the development process we found out that high concentrations of salts, resulting from the Kaumera extraction process, were hindering the material development. Samples with washed Kaumera performed better in field test than non-washed samples (also see below).

Material level

In figure 4 a sample is shown of the bio-composite Re-plex.

	Ingredients	Amount %
Binder	Kaumera	33
Fibre	Recell	25
Filler	Powder from plant source	5
Additive	Citric acid	27
	Glycerol	6
	Tap water	4

Table 2. Ratio between components for Re-plex.

Figure 4. Re-plex bio-composite sample.

Composition and production

Table 2 gives an overview of the ratio between the components.

Re-plex is produced with hot pressing. During this production process the material is placed in a mould which is heated and closed under pressure. Pressure and heat are maintained until the material is cured. Temperature and time for curing Re-plex were determined by experimentation. The production process consists of several steps:

1. Resin and dough preparation
   First a resin is prepared from Kaumera, citric acid, glycerol and tap water by kneading these ingredients for several hours at room temperature. Subsequently Recell and the organic powder are added to the resin and kneaded at 90°C to obtain the dough. This dough is placed in the mould.

2. Hot pressing
   The mold is pressed at 140 °C and at 150 kN for 10 minutes. Subsequently the pressure is released to degasse the sample and repressed at 20-30 kN for 1.5 hours to cure.

Technical material properties

In table 3 the values for the tensile strength and modulus are given as a result of the three-point bending test. The table also shows these values for other comparable biocomposites. The tensile strength is still low, but the modulus is in the higher range.

The fire test showed good performance of the material when exposed to a butane flame. During the first two minutes some enlarged

Material	Tensile strength (MPa)	Modulus (GPa)	Strain (%)	Reference
Re-plex	7	2.7	0.3	
PHB+ sawdust	21	3		(Cinelli et al., 2019)
PHA+ cellulose micro fibres	23	0.9		(Cinelli et al., 2019)
PLA+ banana	18.5	1.5		(Rajeshkumar et al., 2021)
PLA+ coir	14	4.4		(Rajeshkumar et al., 2021)

Table 3. Tensile strength and modulus for several biocomposites.

flames were visible. Afterwards, charring of the sample started. During the test, no dripping or visible fumes occurred. At minute twelve, about 50% of the sample was charred and had broken off the entire sample (figure 5).

Figure 5. Fire resistance test

For the biodegradability test, the material kept its shape for seven weeks. The weight of the samples increased after submersion and stayed constant afterwards. Algae grow appeared on the canal water samples and for the tap and saltwater tests fungus formations appeared in the water (figure 6). The weight measurements show that the material does not degrade immediately, but the microbiological activity indicate that it will biodegrade eventually.

Figure 6. Fungus growth in tap and salt water respectively and algae growth on sample from canal water.

Experimental material properties
The outcomes of the experimental test can be summarized as follows:

- On a performative level most people picked the material up and smelled it;
- On a sensorial level people found it a rigid, but weak material, with an irregular surface.
- On the affective level the smell and weakness were named as disturbing qualities. The material broke much easier than the participants had expected. On the other hand, they felt curious about the unfamiliarity of the material.
- On an interpretive level Re-plex was judged futuristic. Furthermore, Re-plex look and feel were judged as natural, due to its irregular surface and warm and smooth touch. These qualities were appreciated. Also, the story behind the material (i.e. being a material from wastewater) increased the positive appreciation of the material.

Product level
The biodegradability, fire- and water-resistance, and good strength are distinctive properties of Re-plex. With these in mind the brainstorm sessions yielded two initial applications for further testing, i.e. nature restoration in aquatic settings and façade cladding. Both applications were tested and developed in collaboration with a market party. Figure 7 gives an overview of the design and tests.

When producing the prototypes for the field tests it became clear that the brittleness of the material is a serious problem. Many of the beams for the 3D structure for nature restoration already broke during assembly, therefore less test environments could be tested than planned for. For the façade panels, the initial plan was to create 3D structured tiles. However, we were unable to structurally release these from the mould. Therefore flat and smaller samples were created.

Furthermore we could integrate an improved version of Kaumera, i.e. washed Kaumera, in this field test as well (also see Feedstock level).

	Nature restoration	Façade panels
Design		
Description	3D structure to support young plant growth in an aquatic environments. As soon as the plants take root, after 2-3 years, the support structure becomes redundant and should degrade without harming the environment.	Tiles for façade cladding to support biobased building. The tiles are made with washed and unwashed Kaumera and coated with Linseed oil and 2KPU Varnish.
Based on material properties	o Water resistance o Biodegradability o Strength	o Water resistance o Fire resistance o Strength
Test environment	o Dutch salt water (Voordelta) o Dutch fresh water (Vechtplassen)	o Living lab location Amsterdam (Bajeskwartier)
Test parameters	o Speed o Modus of biodegradation	Influence of weather on o Structural (degradation) performance o Aesthetic (changing colour) performance

Figure 7. Overview of design and tests for field tests.

Field tests

The field tests are still ongoing and the samples are under observation. Figure 8 and 9 give an overview of the samples at the start and after respectively 6-8 months and one month. The samples for nature restoration are broken after 6-8 months, but they kept their shape. In fresh water, algae growth appeared on the surface and in salt water, the samples eroded.

The façade panels show a significant difference between the washed and unwashed samples after one month (figure 9). The non-washed samples started leaking and the sample coated with linseed oil leaves traces when touching.

On the contrary, the washed samples with both the linseed oil and 2KPU coating are still in rather good shape. Observation after one month took place after rainy weather and a notable smell was detected for all samples.

Discussion and Conclusions

The goal of this paper was two-fold. First to introduce FMP-combinations, and secondly to apply this to the development of Re-plex. Both topics are discussed below.

Figure 8. Field test with Re-plex for nature restoration.

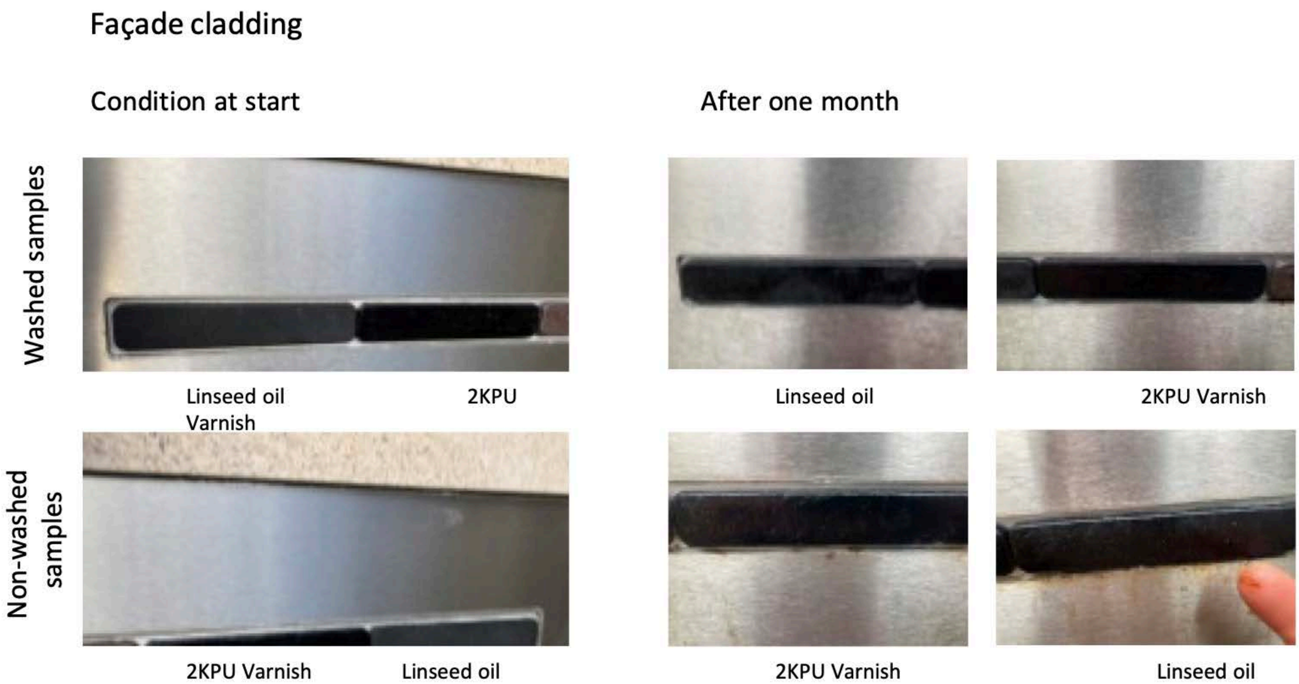

Figure 9. Field test with Re-plex for façade cladding

FMP-combinations
Approaching the development of bio-based materials for a circular economy as an FMP-combinations places the material in a broader context. Due to early material testing and prototyping with an initially sub-optimal material, all levels can inform each other for improvement. This helps to steer the which properties are required to meet the envisioned product lifetime and high value recovery. Therefore a better understanding is obtained of how the material can be used and should behave in a circular economy.

Re-plex
With the development of Re-plex, we prove the value recovery of a major organic waste stream. Due to the iterative process between feedstock, material and product level, we could extend the lifetime of an organic waste stream into a high value material for which interesting applications were found with market parties, i.e. façade panels for the building industry and 3D structures for nature restoration in aquatic settings. We could identify these applications early in the development process based on initial properties. The nature restoration structures exploit the biodegradability and strength of Re-plex, where the façade elements exploit the fire retardant properties of Re-plex. The field tests gave insight into the feasibility of the material for the envisioned product lifetime. For nature restoration this looks promising as microbiological activity and/or erosion took place on the samples, and despite breaking, the shapes are still intact after (more than) half a year. However, the brittleness and reproducibility remain a challenge for both cases and this requires further development. Hence returning to the feedstock level to further improve Kaumera by washing. This already indicates promising results for the façade panels on product lifetime as the washed samples are in significantly better condition than the non-washed samples after one month.

We would like to state that approaching Re-plex as an FMP-combination resulted in valuable applications that include sustainable resources and promises material optimisation towards appropriated lifespans.

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