Production and composting of waste-filled biofilms as a sustainability educational experience for a secondary school setting

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Abstract
Problem. Waste upcycling is often seen as a scattered concept, difficult to be put into practice in an educational yet scientific context. Objectives. The idea is to provide an educational experience able to supply the students a wider perspective over how waste can be brought back into the productive system, until at all possible not Methods. Outsourcing and characterization of waste, production of biofilms, home composting experiments. Results. The experimentation gives a practical view of what is meant by circular economy moreover suggesting ideas about possible options for selecting waste and starting characterizing it. In particular, it offers indications about the scientific method for testing materials including waste and being aware of their end-of-life, which all have influence on sustainability of the process. Implications Ideally, depending on the time allotted for experiments, the work can be repeated iteratively to improve the results. Also, a database about possible local waste for DIY production of bioplastics can be generated over time, including considerations about ease of outsourcing, availability, seasonality, etc.

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1. Introduction

The growing awareness of the environmental impact of human activities has brought attention to the need to develop effective strategies for reducing the carbon footprint. In this context, the "three Rs" (reduce, reuse, recycle) represent a deeper reflection on the end-of-life of the object. Understanding how to effectively reuse and reduce waste is essential to fully embrace sustainability (Santulli & Lucibello, 2018). To bring children closer to environmental issues, it is essential to encourage responsible behaviors that extend from the school environment to the entire community. As proposed by OMEP (World Organization for Early Childhood Education) in 2010 in a broader context through the 7Rs (Reduce, Reuse, Respect, Reflect, Rethink, Recycle and Redistribute) represent a tool for understanding and putting into practice strategies for sustainable development (Santulli et al, 2020). Also, a circular economy model that aims at more sustainable development and a balanced society integrates economic, environmental, technological and social aspects in a balanced way, considering their interactions at all levels, from the entire economy to individual industrial processes (Ghisellini et al, 2016). In this sense, the production of DIY materials from waste (or else, "secondary raw materials") does represent an experience that can be realised in a school setting (Rognoli, et al, 2015). This will allow children familiarising in a simple way with waste, underlining its importance and enabling reasoning over the possibilities offered by its recovery, on the other hand easily and practically learning the experimental method for materials' development (Fathurohman et al, 2022). The University of Camerino, in connection with various schools, has carried out, over the years, experiments to train students to the production of DIY materials using waste, also to correlate the process with eliciting a possible "design value" for waste (Santulli et al, 2017). Over time, the exigence has come though to summarise into a single and coherent route comprising various experiments and learning strategies to clarify the significance of the process of "bioplastic creation from waste" for introducing school pupils to circular economy and sustainability.

In this light, this article explores the educational potential of bioplastic films, obtained from waste of natural origin by giving new life to materials such as spent ground coffee, turmeric waste, kenaf and hemp fibers, using a simple matrix formed by cornstarch, glycerol and vinegar. The creation of biodegradable materials from what would otherwise be discarded not only suggests a concrete alternative to traditional plastic, but also paves the way to a deeper understanding of the life cycle of materials, stimulating creativity, innovation and critical environmental awareness, through an understanding of the experimental method. The study discusses the feasibility and the limitations, in educational terms, of the procedure carried out, through the direct experience of the authors, and the possible developments and further possibilities, in view of its application in the schools.

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2. Method

2.1. Aims of the experience

The principal goal of the experience is promoting critical environmental awareness by allowing the children to understand the value of waste: when waste is recognised as possessing an expressive and potentially economical value, it is brought back in the economical system, therefore potentially realising a circular economy. However, not all types of waste can be managed into a school setting: the main points concern their limited dimensions (powder or short fibers), which allow these to be processed, and their absence of harmfulness.

Studies on the inclusion of waste into a material are aware of the fact that, while refuse needs to be included, above a certain quantity it will start degrading the properties of the hosting material. In the case of DIY bioplastics, (a) mixing it with waste will to a point increase its properties, yet (b) it might affect its degradation at end-of-life, making it less sustainable. For this reason, a “recipe” needs to be developed that enables both aims to be reached, and this will be done by “trial-and-error”, discussing the results obtained at every experiment and assessing which composition appears to be the most suitable. Figure 1 is a schema that summarizes the structure of the experiment.

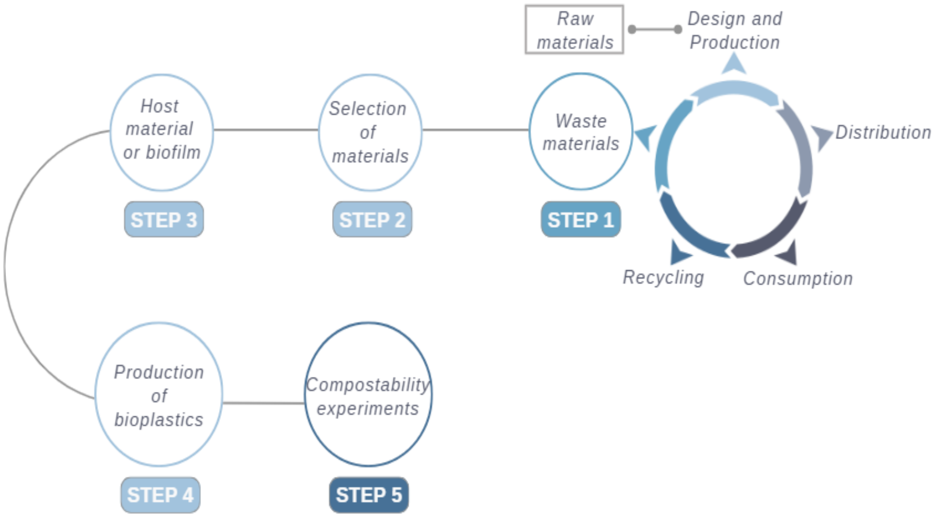

Figure 1. Schematic of the Structure of the Experiment

2.2. The structure of the experience

2.2.1. Waste selection

For the first tentative activity, four different waste types have been proposed, which are represented in Figure 2. They are namely: Hemp fibers (H), Kenaf fibers (K), Spent ground coffee powder (C), and Turmeric powder (T)

These four types of waste have distinct characteristics, which can be illustrated in terms of their properties and to them belonging to a complex production system: this is once again the object of explanations that accrue the educational content of the experience.

Hemp is a traditional agro-food and textiles (ropes, garments, wood replacement, medicals, flour) productive system, which has been brought back into Italy during last decades and in view of its possible reintroduction, a circular economy approach needs to be implemented by valorising even its residue (Giupponi et al 2020). In a similar position is kenaf, which is mainly diffused in Malaysia, and represents another possible natural fiber for exploitation (Austin et al, 2024). Comparing the results obtained with the two different fibers in the production of biofilms can be a further objective of the project.

Spent ground coffee powder is of widespread diffusion, as from the coffeemaking tradition by espresso machines. It is a ligneous waste, which has found large use into various fields, such as design (Aguiar et al, 2024) and materials science (García-García et al, 2015), for its large availability and compostable nature that suggested also its application for soil amendment (Bomfim et al, 2022). Finally turmeric was proposed as a typical anti-mold agent, which is required when bioplastic from a polysaccharide base are produced: the antibacterial properties of turmeric have been reported (Odo et al, 2023), which also enabled its extract to be used as a dye for natural fibers, such as silk (Sadaf et al, 2024).

2.2.2. Biofilm production

To create the host material, or biofilm, for the introduction of the different types of waste, materials no longer suitable for the agrofood (residual or expired) were used. In particular, wine vinegar was used, which contains approximately 6% acetic acid per liter of product, corn starch and glycerol.

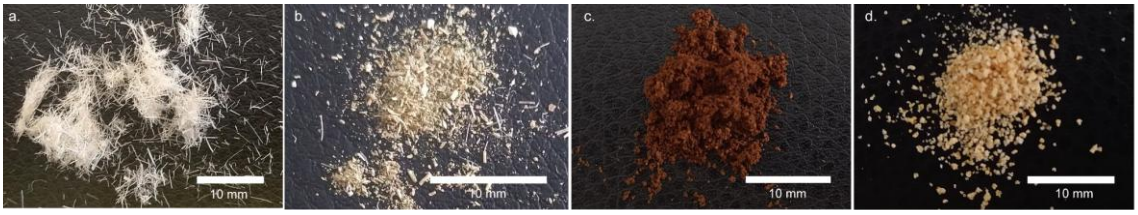

Figure 2. Waste materials.
a.) Kenaf fibers; b.) Hemp fibers; c.) Coffee powder and d.) Turmeric powder.

The base material for introduction of waste was produced by using small spatulas, in which 3 g of corn starch were inserted into a beaker with 25 mL of distilled water. After carefully stirring the components, 3 g of glycerol and 3 mL of vinegar were added. Once a milky compound was obtained, the beaker was placed on a heating plate with T≈100 °C for 30 minutes, making sure that the mixture does not boil. During this phase it was possible to observe the separation of the components according to the density, for this reason it was necessary to mix frequently avoiding the formation of lumps. Once a sufficiently dense solution was obtained, which detached from the walls of the beaker, it was removed from the heating plate and the filler was added. Increasing concentrations of filler were created to evaluate the dispersion and holding capacity of the biofilm. As in any materials science study on composites, biofilms with a minimum of three different concentrations of fillers were produced and compared with the bare starch-glycerol-vinegar matrix.

To spread the compound, a wooden mask was created, in which the biofilm was poured and spread with a spatula, leaving a molding cavity of 70x35 mm. In this way, it was possible to cast on the support approximately the same quantity of product, obtaining a constant thickness and observing its shrinkage. After three days from application, the biofilms are superficially dry but with a high internal water content. At this point, the edges were lifted with a spatula and a weight was placed on the PVC or glass countermold to prevent the biofilm from wavy during the shrinkage phases.

As regards the support for the laying of biofilms, a preliminary experiment was carried out, in which untreated and treated wood, aluminium, film, baking paper, glass, and semi-rigid plastic were tested, the latter proving to be more ideal for avoiding contamination and removing the material more easily. All the details about biofilm fabrication are reported in Figure 3.

About the amount of waste filler to be introduced in the biofilms, three concentrations were selected, namely 0.1%, 0.3%, and 0.5%. These amounts were tentatively proposed to adapt to all fillers and in the understanding that packaging films possibly adapted to food use would only accept the inclusion of small amounts of filler/waste: examples are reported in (Muñoz-Gimena et al, 2023). In Figure 4, biofilms detached from treated wood and rigid plastics were compared, it is visible that the edges of the latter appear more regular, facilitating the potential cutting towards a precise rectangular geometry. Once established which is the most suitable support (rigid plastic), in Figure 5 the other biofilms without and with the other fillers (hemp fibers, spent ground coffee, and turmeric) are reported to assess the uniformity of their distribution. The degree of contraction, as shown from the figures, is variable depending on the amount of fillers: it can be noticed that the more compact structures are obtained with kenaf fibers and spent ground coffee, even at 0.5% filler, while uneven surfaces are reported in the other cases. It might be suggested that in these two most fortunate cases the introduction of a higher quantity of filler would be even possible.

In Figure 6, observations were carried out with the acquisition of high-resolution images under an Euromex EduBlue Stereo Microscope with 10x magnification in transmitted light, to complete the picture about the uniformity of the distribution for the various fillers. In addition, microscopical investigation can offer indications over the circularity of the particles, and the aspect ratio (length/diameter) of the fibers. for the sake of microscopical study, also a hybrid composite was produced including alongside spent ground coffee and turmeric powder.

Figure 3. Biofilms creation.
a.) solution on a heating plate; b.) pouring biofilm into the mask; c.) spreading with a spatula; d.) edges were lifted with a spatula and e.) dry biofilms.

Figure 4. Kenaf fibres-filled films laid on treated wood (a., b., c., and d.) and plastic (e., f., g., h.)
a.) and e.) biofilms without filler; b.) and f.) 0.1 % kenaf filler; c.) and g.) 0.3 % kenaf filler; d.) and h.) 0.5 % kenaf filler.

Figure 5.Films with Spent Ground Coffee, Turmeric and Hemp fibres.
From right to left: a.) 0.1 % coffee; b.) 0.3 % coffee; c.) 0.5 % coffee; d.) 0.1 % turmeric; e.) 0.3 % turmeric; f.) 0.5 % turmeric; g.) 0.1 % hemp; h.) 0.3 % hemp; i.) 0.5 % hemp.

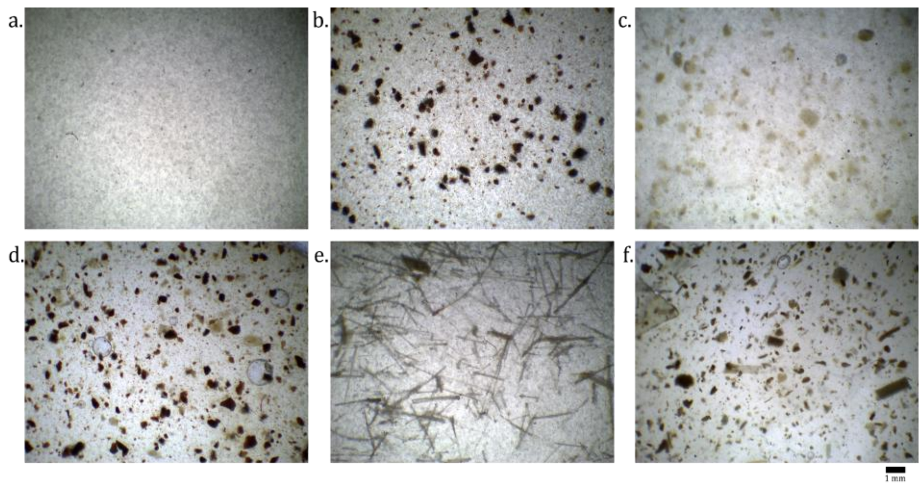

Figure 6. Optical microscopic observation of biofilms.
a.) Biofilm without fillers; b.) 0.5% coffee filler; c.) 0.5% turmeric filler; d.) 0.5% coffee and turmeric filler in equal parts; e.) 0.5% kenaf filler and f.) 0.5% hemp filler.

2.2.3. Home compostability experiments

To investigate the end-of-life of the biocomposite realised (bioplastic + fillers), home compostability experiments were also carried out. Control samples constituted by the bare bioplastics wer also provided. One seedbed was dedicated to containing acidic soil and one to containing alkaline soil in the understanding that pH of soil does vary from 3.5 to 10.5 (Anunciado et al, 2021). In both trays the drainage holes were blocked with tape. One seed tray was dedicated to the containment of acidic soil and one of alkaline soil. The pots were then filled with universal soil that is reported having pH=7. Two conditions were simulated: the acidic one and the alkaline one. For this purpose, in the former case, to lower the solution pH, an appropriate amount of lemon juice (containing approximately 5-8% citric acid) was added to the soil until it reached pH=5. Conversely, to obtain alkaline soil, sodium bicarbonate was added in the right amount until it reached pH=9. The measurements were carried out using Dual-Tint, pH-Dispenser, pH 1 - 12, as reported in Figure 7. Since the compostability characteristics of bioplastic can only be modified by the introduction of the fillers, these experiments were especially carried out on the samples that were containing the maximum amount of filler, hence 0.5%. In practice, in each slot of the trays, a biofilm with a different filler at the same percentage was inserted, cohesive to the wooden stick on the upper end with double-sided tape so as not to contaminate the entire biofilm with glue. The selected biofilms were cut using scissors. Before being inserted into the soil, the sticks with their biofilm were weighed to evaluate the weight loss during the conditioning period (after two, three and four weeks, to simulate the whole duration of the composting period, which involves the destruction of 95% of the biofilm mass after six months). The biofilm has been bonded on both surfaces of the stick and was inserted in the center of the pot filled with soil. The one-month limit of the experimentation proposed needed also quantitative measurements, not easy to perform for the fragmentation of the film, as depicted in Figure 7 c and f, though it is possible to indirectly measure it by weighing the increase in weight of the supporting stick to measure how much of the film was still bonded to the support after a given amount of time. Other limitations are in the fact that a number of repetitions of the test are needed, which could be possible in the case that larger groups of pupils are involved in the experimentation.

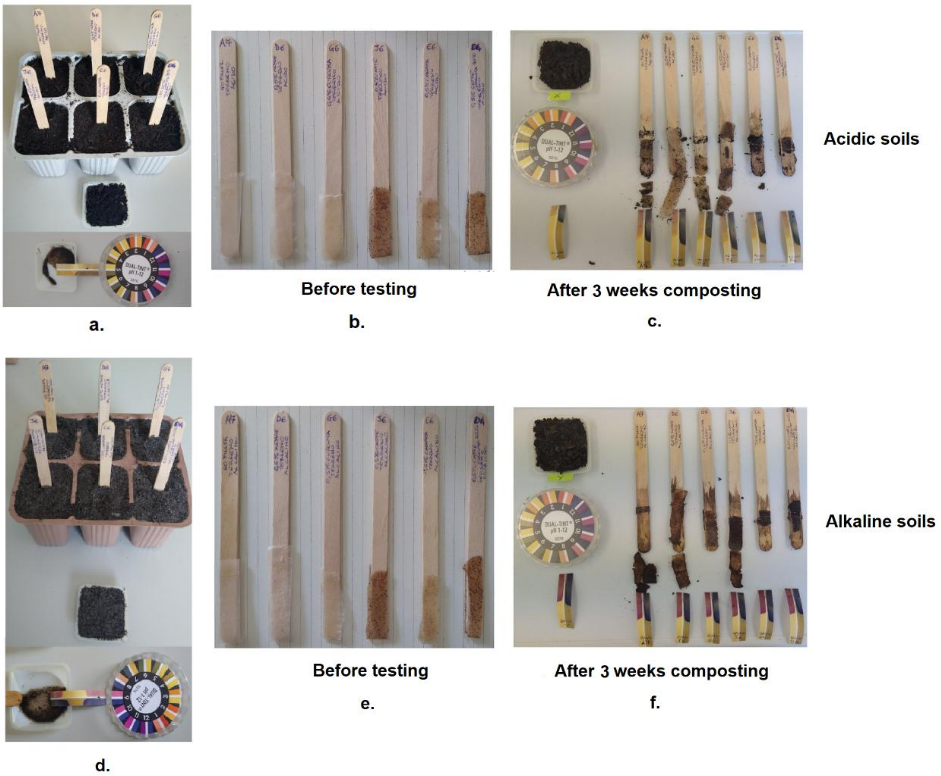

Figure 7.Compostability tests.
To the left the preparation of tests, to the center the samples before testing and to the right the samples after extraction (three weeks)

3. Results and Discussion

The sequence of experiments were set to offer students a visible experience of an important aspect of sustainability, which is the possibility to reinsert waste into the productive system, therefore giving them back a function and therefore a value. This is the principal characteristic of a circular economy approach, considering that the first worthiness of a material is a psychological one, that makes us familiarising with it (Romero-Hernández & Romero, 2018). The abilities required to the students are limited, not beyond simple manual skills with the use of a few devices, such as scales, cutters, heating plates, blenders, simple pH indicator, and optical (digital) microscopes, which are among the common tools available in any science lab.

The option here selected to achieve this objective is to solidly locate them as a filler into a host material, which is a starch-based biofilm. This is considered as compostable (disposable as to be used in the soil as fertilizer), which could be further subjected to evaluation according to standards such as European Regulation EN13432. However, it is worth noting that the aforementioned norms do concern industrial compostability: for training purposes though (and for the present experiment), home composting has a significant value, especially as the implementation of a "good practice". In the introductory part, its importance will be emphasized, through the presentation of some experiments available in literature (Solano et al, 2022).

The environmental value of the experiments can be indicated by some different themes, which are discussed here below:

a. Production of a starch-glycerol-vinegar (with some water) as the “host” matrix for waste. In principle, this combination of materials cannot be considered as secondary raw materials. However, some improvements can be foreseen in the long run, which have not been initially contemplated. This could include using expired starch and vinegar, the starch-rich water from rice cooking, which has been only proposed for use so far to produce bio-ethanol for low-cost motor operation, in competition with wheat straw waste (Swain et al, 2019). Another possible development is suggesting the use of botanical glycerol extracted from plants, such as Silybum marianum, an abundant invasive species in Italy, especially in the South (Jabłonowska et al, 2021).

b. Identification of the “personality” of the single waste, hence of the possible “likeability” in a circular economy process. Refuse needs to be in principle disposed of at “zero km” (Colajanni et al, 2023). In our case though also kenaf was used, which is not local, reasoning of its possible introduction in Italy, which had some attempts in the past, only partially successful, also for the limited appeal of the various products (Ayadi, et al, 2017). In general terms, though, the selection and introduction of waste does also represent a multidisciplinary reflection on the economical system that produces that waste and how refuse generation can be reduced, if not nullified, in that context, which practically results in proposals for a EoW strategy (Andika et al, 2025).

c. As opposed to plastics, DIY “bioplastics” do not have a uniform color, are changing of appearance and degrading with time. This raises the awareness that, if we have to move away from using synthetic materials, we have to accept a visible ageing process, which might in the long run generate phenomena related to biological attack, such as e.g., mold (Rognoli et al, 2020). On the other hand, the presence of a scent in the material can also add to its personality: the fragrance can be modified by the addition of other waste, giving rise to “odorful materials”, which is an essential difference from traditional plastics. This therefore becomes an essential factor in possible acceptance of the refuse-filled materials, and generally on bioplastic films, and can be modulated by the use of appropriate e.g., herbs, or extracts, always to be intended as by-products of some economical system (Azmin & Nor, 2020). The scent can also be corrected by mixing different types of refuse/filler. In more general terms, it needs to be highlighted that hybridization of different fillers in a “host” materials would allow tailoring its properties and it is a practice widely accepted in materials science whenever possible, to introduce the maximal amount of secondary raw matter in the matrix. This is by no means limited to the production of DIY bioplastics, but it is a concept that strongly applies in sectors in search for a wider idea of sustainability, which involves the diffuse application of waste from the same and other productive fields, such as construction industry (Vigneshwaran et al, 2019; Kamble & Behera, 2021).

d. The study of home compostability appears quite easily reproducible, though with some important limitations. First, it is not possible to ensure by the methods used, the constancy of the pH value. The values may be influenced by the dissolution of bioplastic, which is as a whole a weak acid, although its effect might be limited if the amount of it used on the sample is much lower than the volume of soil on which the test takes place.

In general, it is suggested that the sequence of experiments presented allows familiarising with different types of waste and with their respective effects on the host material. For visualisation’s sake, to analyse the different morphological characteristics of waste, the quantity introduced is preferably limited, which requires precise measurements. Furthermore, the recipe of host material would be needed to allow some transparency.

4. Conclusion

The study highlighted the potential of production and composting of DIY “bioplastics”, based on self-developed thermoplastic starch for a better awareness of the different types of waste that are available for re-introducing in the materials sector, therefore avoiding combustion for energy recovery. In principle, a large number of powdered or fibrous refuse can be simply recognised and analysed in a kind of sensory experience, which enables a simple and factual approach to a concept of circular economy with basic experiments, requiring basic tools normally available in school labs.

Author Contributions

Greta Vicentini: Conceptualization, Methodology; Writing - Original draft preparation; Sara Mattiello: Conceptualization, Methodology; Writing - Original draft preparation; Carlo Santulli: Conceptualization; Supervision; Writing - Reviewing and Editing. All authors have equal contributions to the paper. All the authors have read and approved the final manuscript.

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Declaration of Conflicting Interests

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