DOI: 10.62897/COS2025.3-1.218

10-12, November 2025, Győr

OVERVIEW OF THE ENVIRONMENTAL IMPACTS OF PLASTICS IN WINDOW MANUFACTURING

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Plastic window production is a key segment of today's construction industry, with significant economic, environmental and social impacts. PVC, as the most widely used raw material, dominates due to its favorable price-performance ratio and good physical properties, however, its production and waste management pose a serious environmental burden. The aim of our research is to investigate the replacement of PVC parts or their complete replacement with more environmentally friendly polymers, with particular attention to the possibilities of biopolymers and recycled plastics (r-PVC). During the analyses, we assessed the performance, economic viability and life cycle impacts of alternative materials. Based on our results, biopolymers in their current form do not meet the technical requirements for windows and doors, while the use of r-PVC proved to be the most promising solution from both an environmental and economic perspective. The study highlighted that recycled PVC provides broader industrial support for strengthening the circular economy and achieving social sustainability goals.

1. Introduction: Requirements for window materials

The window, as a product, consists of several components, this section will focus only on the materials of the window frame and the requirements for it. The frame materials include various types of wood, plastics, of which PVC (poly(vinyl chloride)) is the most important, aluminum profile window frames, metal profiles, especially steel or stainless steel frames, and composite frames (Jevtoska, 2008; Gustavsen et al., 2007).

Similar requirements apply to window frames, regardless of the material, although the fulfillment of these requirements varies depending on the type of material, so when choosing a window it is worth considering which requirement it is most appropriate to meet. Focusing on plastic windows, the requirements listed below should be taken into account (Jevtoska, 2008; Gustavsen et al., 2007).

Good thermal insulation is important for windows. According to the latest regulations (9/2023 (V.25.) ÉKM Decree), the following applies: the thermal transmittance requirement for facade glazed windows with PVC frame structures larger than 0.5 m2 is 1.1 W/m2K.

In the case of resistance to environmental influences, several effects must be taken into account, one is UV resistance and the other is water resistance. This is important in the case of plastic windows, as high levels of UV radiation and moisture absorption can cause serious problems, including deterioration of mechanical properties.

The mechanical properties of the material are of paramount importance; the frame must be able to withstand the load and must be sufficiently rigid. In order to avoid the tendency to warp, this can be improved with a steel insert (PVC sashes also have a metal insert, see Figure 1). However, it is important that the steel insert only comes into contact with the plastic, as it insulates and prevents thermal bridges (parts of the enclosing and window and door structure where, due to the geometric shape or the use of materials, a multidimensional heat flow and temperature distribution occurs).

Nowadays, a problem with plastic windows and doors is that they are too airtight and do not have the minimum natural filtration that is found in wooden windows. Therefore, small vents are usually built into them to achieve natural ventilation, which can also be seen in Figure 1.

Figure 1: Small vents for air circulation (Aikondistribution, 2025)

For all doors and windows, aesthetic aspects, external and internal appearance, maintainability, and the costs involved are important, which are small for plastic doors and windows compared to the maintenance requirements of wood. Also, the price is an important aspect, PVC doors and windows can currently be purchased at very reasonable prices. The price of wooden windows is several times that of PVC.

2. Applicability of biopolymers for window frames

2.1 The biopolymer

According to the European Bioplastics Association, any plastic that is biobased, biodegradable, or both, is called a biopolymer. In this definition, the term biobased means that the polymer is produced partly or entirely from renewable plant resources. By biodegradable, we mean that when composted or placed in a biotic environment, the polymer breaks down into invisible natural components, such as water and carbon dioxide, within a few months or a few years at the latest, thanks to the decomposition ability of fungi, bacteria or even algae. Thus, it does not harm our environment and does not pollute the compost (Tábi, 2021; European Bioplastics Association, 2025).

Based on their origin and degradability, polymers can be classified into four categories, as shown in Figure 2. Of these, three groups can be said to meet the criteria for biopolymers, albeit to different conditions. The term biopolymers is mostly used for polymers that are made from renewable resources and are biodegradable.

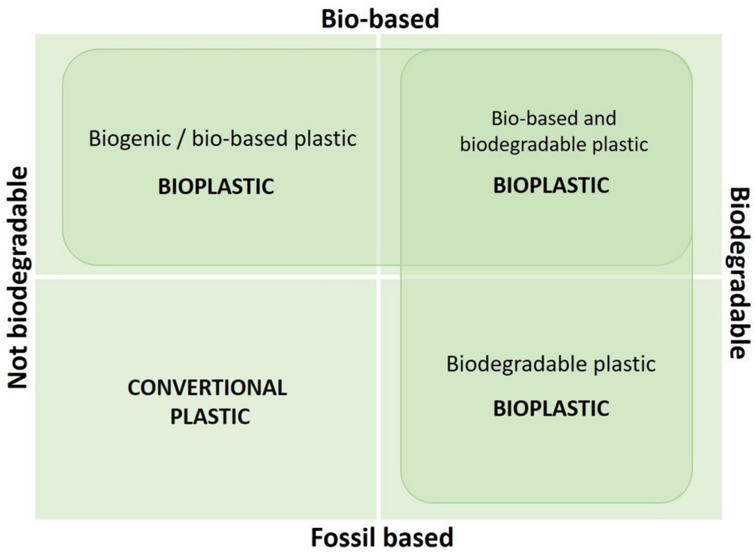

Figure 2: Grouping of polymers (Tábi, 2020)

2.2 Testing the applicability of biopolymers

In this section, we will go through the requirements for window frame materials by examining biopolymers.

Thermal conductivity/thermal insulation capacity

The thermal conductivity of biopolymers is influenced by the type of material used, but overall they have good thermal insulation properties and low thermal conductivity. The low thermal conductivity is due to the proteins and polysaccharides in the polymers, which do not conduct heat well. This is because biopolymers are amorphous, and do not have the crystalline structure necessary for efficient heat transfer, such as metals or some synthetic polymers. The thermal conductivity of biopolymers can vary depending on the composition, but is generally lower than that of conventional plastics (Phiri et al., 2023; Karkri, 2017).

Resistance to environmental influences

Temperature

At low temperatures, biopolymers tend to become rigid, which can reduce their flexibility and make them more brittle. The temperature behavior depends on the type of biopolymer, but in general, the structure of biopolymers becomes stiffer in response to a decrease in temperature, which can affect their application. At high temperatures, biopolymers tend to dehydrate, degrade or liquefy, especially if they are not sufficiently stable (Avérous and Eric, 2012).

Humidity and moisture content

Biopolymers are often hygroscopic, meaning they can absorb water from their environment. Water absorption increases the volume of biopolymers and can change their mechanical properties. High humidity can reduce the stiffness of biopolymers while increasing flexibility, but it can also promote biodegradation (Avérous and Eric, 2012).

UV radiation

Biopolymers can be degraded by UV radiation, they are sensitive to UV light, which can lead to changes in their molecular structure, reducing their mechanical properties (such as strength and elasticity). UV radiation can also cause oxidation processes that destroy the structure of biopolymers (Avérous and Eric, 2012).

Mechanical properties, stiffness

It can be generally stated about biopolymers that their mechanical properties depend on environmental influences (temperature, moisture and humidity). Since in this case the polymer would be exposed to significant environmental influences during application, the pre-designed mechanical properties could change significantly during application (Avérous and Eric, 2012; Sadasivuni, et al., 2020).

Price

The cheapest biopolymer is twice the price of PVC plastic, so according to the current state of science, among many other aspects, it is not worth considering the use of biopolymers in window frame production as a material choice option (Plastic News, 2025). Overall, it can be stated that the use of biopolymers is not widespread in window production, which is due to the unfulfilled properties presented above. Their development is still ongoing. In addition to biopolymers, recycling is also worth considering when searching for alternative materials for window frames.

3. Using recycled plastic

A study by Stichnothe and Azapagic (2013) shows that significant environmental resources can be saved by using recycled PVC instead of new for window frames. Replacing virgin PVC with post-consumer PVC saves 2,056 kg/t CO2. Considering that the global annual consumption of PVC for window frames is approximately 3 Mt and 200 Mt of frames are in use, the potential greenhouse gas emissions and other resource savings are significant. Based on the results obtained in this study, recycling 100,000 t of window frame waste per year in Europe could save approximately 200,000 t of CO2. Recycling PVC reduces the amount of waste going to landfill and/or incineration. The latter is particularly controversial, as it raises health concerns due to the potential formation of dioxins during the incineration process (Stichnothe and Azapagic, 2013).

3.1 Recycled PVC (r-PVC) options

Mechanical recycling offers a sustainable solution for PVC waste management, enabling the production of high-quality products. The study by Khouya et al. demonstrates that durable window profiles can be produced using 100 % recycled PVC. Experimental and numerical analyses confirmed the excellent mechanical properties of recycled PVC, including a tensile strength of 42.34 MPa and a flexural strength of 3,556.42 MPa, making it a strong candidate for replacing virgin plastic in construction materials. The experimental results were validated by numerical simulation, which confirmed the performance of the recycled PVC profile. Overall, recycled PVC proves to be a viable, environmentally friendly material for sustainable architecture, balancing mechanical performance, thermal stability and environmental benefits (Khouya, et al., 2025a).

Sebbar et al. (2025a) focus on the latest developments in the field of windows, with a particular focus on the mechanical and thermal characterization of PVC and recycled PVC profiles. The results obtained show that PVC and recycled PVC profiles exhibit remarkable mechanical strength and good thermal resistance, as evidenced by a softening temperature of 80.55 °C and a heat recovery percentage that meets the standards. Recycled PVC boasts excellent dimensional stability with a heat recovery of 0.5 %, indicating robust performance even in environments exposed to temperature fluctuations. However, further optimization of the formulation and manufacturing process is essential to achieve optimal performance, especially in terms of mechanical strength, especially for recycled PVC (Sebbar, et al., 2025a).

Recycled PVC is usually used to form inner layers, the outer layer is a new PVC layer, this is important due to aesthetic considerations as well as weather resistance requirements (Figure 3). Using the co-extrusion method, the window and door structure is made entirely of r-PVC on the inside, and on the outside, it is covered with a raw PVC coating to meet aesthetic expectations.

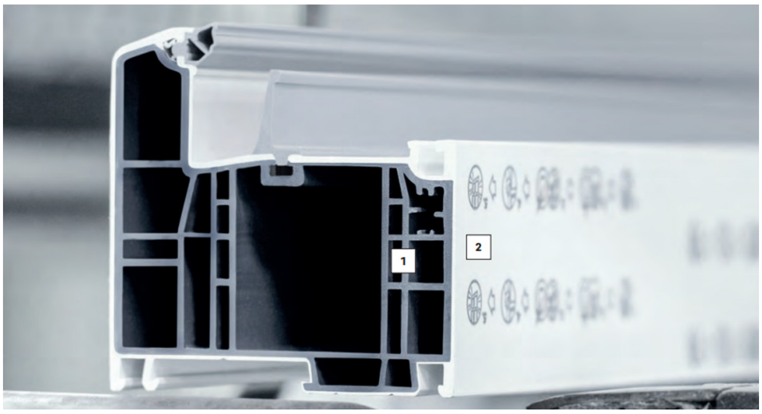

Figure 3: Cross-section of Rehau recycled PVC windows (REHAU, 2025)

4. Current research into the applicability of PVC and r-PVC as window frames

The aim of the research by El Hassan Sebbar et al. is to evaluate the thermal performance of window frames made of recycled PVC, which is a key factor in improving the energy efficiency and indoor comfort of buildings. The thermophysical properties of recycled PVC were determined experimentally using advanced measurement techniques. The heat transfer through the cross-section of three types of manufactured frames was numerically investigated using CFD simulations based on the finite volume method. The frame surfaces were considered as grey and diffuse surfaces, and adiabatic conditions were applied to the lower and upper horizontal walls. The research compares the thermal performance of the frames with the predictions of the EN ISO 10077 standard and with the results obtained with the 2D numerical approach, ensuring the reliability of the thermal performance simulations. The results include the frame thermal transmittance, thermal conductivity, temperature distribution and air velocity in the frame cavities, which provide a comprehensive assessment of the heat losses. The differences between the two applied thermal conductivity and thermal transmittance calculation methods are analysed and their underlying reasons are also described. The proposed numerical approach can be applied to different geometric profiles and material properties, making it a valuable tool in the design of high-performance window frames (Sebbar, et al., 2025b).

The focus of the research by Oumaima Ait Khouya et al. is on assessing the physical, chemical and thermal properties of the recycled material, with a particular focus on thermal insulation performance. By comparing these results with the specifications of standard and virgin PVC, the study provides critical insights into the homogenization process and evaluates the suitability of recycled PVC for high-performance window profiles, offering a promising approach for material reuse in advanced industrial applications (Khouya, et al., 2025b).

4.1 Thermal performance, environmental impacts

In order to improve energy efficiency, Sebbar and his colleagues tested three different and modern PVC window frames to experimentally evaluate the thermal performance of recycled PVC window frames. They developed a calculation method to demonstrate the thermal transmittance of frame structures, which even takes into account the air in the chambers (Sebbar, et al., 2025b).

Schmidt and his colleagues highlight in their research that PVC, which was previously installed and is still in use in many places, contains lead. During recycling, the lead is recycled back into production, preventing the material flow cycles from being closed. For these reasons, it is necessary to filter out impurities during recycling (Schmidt, et al., 2024).

5. LCA values of PVC and r-PVC

Chapter 2 The production of recycled PVC is more environmentally friendly than the production of virgin PVC. Uncertainty analysis in Ye et al.'s work showed that virgin PVC has a greater impact than recycled PVC in most categories except agricultural land (Ye, et al., 2017). Based on the studies of Ye et al., Figure 4 shows the dominant environmental impacts for primary PVC and r-PVC. PVC has very significant "Climate change", "Human toxicity", "Terrestrial ecotoxicity", "Marine ecotoxicity" and "Fossil depletion" values compared to r-PVC. This also shows that it is extremely important to increase the proportion of r-PVC in order to reduce environmental impacts (Ye, et al., 2017).

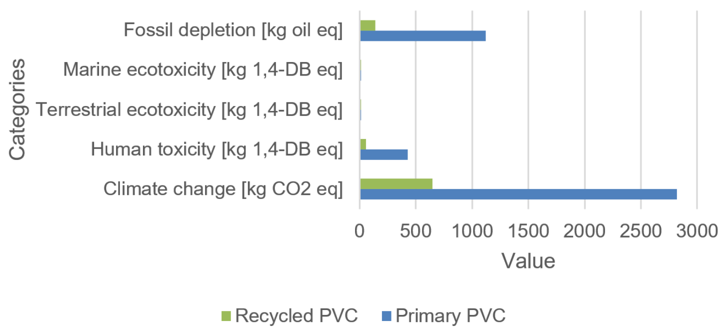

Figure 4: Comparison of the most significant environmental impacts of virgin PVC and recycled PVC (Ye, et al., 2017)

Recycled PVC has an average environmental impact of 85 times less than PVC (Stichnothe and Azapagic, 2013). Figure 5 shows that PVC that has been used once has a much lower environmental impact than raw PVC. This can also be explained by the fact that a lot of energy is used in the production of primary PVC, which does not have to be used again in the case of recycled PVC, and a lot of energy can be saved by recycling.

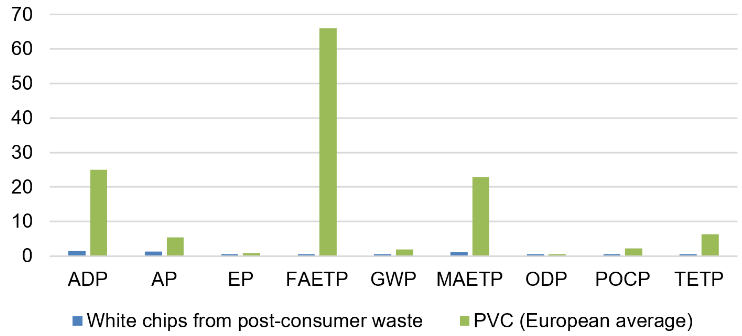

Figure 5: Comparison of „White chips from post-consumer waste" and „PVC" (Stichnothe and Azapagic, 2013)

6. Conclusions

Currently, the use of biopolymers in the production of window frame profiles is not widespread, as traditional polymers such as PVC and fiberglass are much more durable and weather-resistant. Window frames have to serve their users for up to 30-50 y, and biopolymers do not yet achieve this level of resistance. Nevertheless, research and development are underway to use polymers that are biobased or partially renewable. One possible alternative is bio-based PVC, which is produced from, for example, corn, sugar cane or vegetable oils instead of petroleum. This is not yet fully biodegradable, but it could be a more sustainable solution compared to traditional PVC (Table 1).

Table 1: Comparison of PVC, r-PVC and biopolymer for windows (the best: 1, middle: 2, the worst: 3)

	PVC	r-PVC	biopolymer
Cost	1 (x)	2	3 (2x)
Durability	1	1	3
Environmental impact	3	2	1

Another solution is wood-plastic composite (WPC), which combines recycled wood pulp and plastic. This material already exists in the construction industry and is more weather-resistant than purely biopolymer materials. Bio-based polymers such as PLA (polylactic acid) are also being tested, but this material is not yet sufficiently resistant to UV radiation and moisture, making it unsuitable for window frames.
Several factors currently hinder the widespread use of biopolymers, such as durability issues, the cost (twice that of PVC) and the difficulties of recyclability. However, due to the increasing demand for sustainability, it is expected that bio-based polymers or composite materials will appear on the window frame market in the future, at least as a partial alternative to traditional plastics.

However, the use of recycled PVC is proving to be very applicable today. r-PVC is already systematically used in practice by window manufacturers, emphasizing recyclability. Ultimately, it can be stated that the current technological capabilities and the development of the industry allow the possibility of using r-PVC and PVC together. Using r-PVC reduces environmental impacts, while PVC adds aesthetics to window frames. In the future, it would be worthwhile to research the development of more energy- and environmentally friendly proportions of these composite materials, as well as the possibilities of using weather- and UV-resistant biopolymers.

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