

Reduced environmental impact and reuse of materials in dishwashers

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Preface

With the sending of this report, I complete my Bachelor's thesis duties at University West's Department of Engineering Science. The research has developed alongside Asko, whose support and resources have been critical for the development of this study.

Most of all, I want to thank the company and specially, Mikael Johansson, for the opportunity to do this project and for his guidance during the project.

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Abstract

The growing environmental concerns, partly driven by plastic waste, is forcing a reconsideration of the materials used in home appliances like dishwashers, which have considerable numbers of components made up by petroleum-based polymers. While these plastics provide durability, sufficient heat resistance and strength, their non-biodegradable nature leads to ocean microplastic-pollution as well as, the proliferation of landfill wastes, and harmful CO₂-emissions throughout their life cycle. This study therefore aims to identify environmentally sound, recyclable, and bio-based material alternatives that will not compromise the functions and safety of dishwashers but reduce their environmental impact.

In this research, a comparative material selection methodology is employed using Granta EduPack/Selector. With secondary data support from peer-reviewed literature. Conventional materials, mainly Polypropylene (PP). Polyoxymethylene (POM) and Acrylonitrile Butadiene Styrene (ABS), were compared with biodegradable options, such as recycled Polypropylene (rPP), bio-based Polypropylene (bio-PP), Polylactic acid (PLA), and Polyhydroxyalkanoates (PHA). Performance criteria were mechanical-and thermal properties, chemical compatibility, embodied energy, CO₂-equivalent emissions, and recyclability, which were compared using EduPack's Eco Audit tool for life-cycle performance comparison.

The results indicate that recycled Polypropylene (rPP) is the best compromise between mechanical performance and-sustainability, with a saving of approximately 30–40% in embodied energy and approximately 35% of CO₂eq-emissions compared to virgin PP. Bio-PP has better environmental performance but with recyclability limitations at high scales, whereas PLA and PHA have high biodegradability potential for non-structural components, although with lower impact and heat resistance.

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Nomenclature / Glossary

Acronym	Explanation
ABS	Acrylonitrile Butadiene Styrene a common petroleum-based thermoplastic used in appliances.
CE	Circular Economy – an economic system aimed at eliminating waste and continual use of resources.
CO ₂ , CO ₂ eq	Carbon Dioxide – a greenhouse gas measured for environmental footprint analysis. Carbon Dioxide Equivalent – includes also the effect of other greenhouse gases, as if they all were Carbon Dioxide.
ISO	International Organization for Standardization – sets industrial and environmental standards.
LCA	Life Cycle Assessment – evaluation of environmental impacts over the entire life of a product.
MJ	MegaJoule – unit of energy used in embodied energy measurements.
PHA	Polyhydroxyalkanoates – biodegradable polymers derived from biological sources.
PLA	Polylactic Acid – a bio-based polymer made from renewable agricultural feedstock.
PP	Polypropylene – a lightweight, versatile thermoplastic polymer.
rPP	Recycled Polypropylene – polypropylene that has been mechanically or chemically recycled.
rPET	Recycled Polyethylene Terephthalate – a polymer made from recycled PET materials.
SAP	Systems Applications and Products – company database used by Asko AB for materials tracking.
JRC	Joint Research Centre – The European Commission’s in-house science and knowledge service that provides independent scientific advice and support to EU policy.

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Term	Explanation
Circular Design	A design strategy that prioritizes reuse, repair, recycling, and resource efficiency throughout a product's lifecycle.
EduPack	Ansys Granta EduPack (or Selector) – software for materials selection and sustainability analysis in higher education (or research/industry)
Embodied Energy	The total energy required to produce a material, including extraction, processing, and transportation.
End-of-Life (EoL)	The stage of a product's lifecycle after its use, including disposal, recycling, or recovery.
Recyclability	The potential of a material to be recovered and reused in manufacturing processes.

Symbol	Description	Unit
ρ (rho)	Density of the material	g/cm ³
E	Young's Modulus (Elastic Modulus)	GPa
σ (sigma)	Tensile Strength	MPa
λ (lambda)	Thermal Conductivity	W/m·K
EE	Embodied Energy	MJ/kg
CO ₂ eq	Carbon Dioxide Equivalent Emissions	kg/kg
H	Efficiency	%

1 Introduction

Increased global demand for household appliances has led to increased environmental problems related to their manufacturing, use, and disposal. Dishwashers are among the household appliances that are a requirement in present households, as they are easy to use and have water-saving features; however, their life cycle continues to play a significant role in the deterioration of the environment (Fardente *et al.*, 2015). Dishwashers generate environmental consequences through three major stages—production, utilization, and end-of-life disposal. While the largest part portion of the emissions comes from operational energy consumption, the materials employed in production and inefficiencies associated with recycling and reuse are also significant sources of influence (Hischier *et al.*, 2020).

Dishwashers of the current times are composed of a highly advanced combination of metals, polymers, glass, and electrical components, most of which are not designed to be easily separated or recycled. ABS (Acrylonitrile Butadiene Styrene) and PP (Polypropylene) plastics are prevalent because they are long-lasting and inexpensive but are derived from non-renewable fossil resources, have additives, and possess very low percentages of recyclability (Nordahl *et al.*, 2024). Thus, huge volumes of obsolete appliances contribute to plastic pollution and the landfilling of electronic waste (Biganzoli *et al.*, 2016). This calls for the transition to material options that minimize waste, embodied energy, and maximize the product's lifespan.

To address such parameters, circular economy and eco-design principles have become the principal leading approaches in the appliance industry. This encompasses design for product durability with longer lasting, modular, reusable, and disassemblable (Matsumoto *et al.*, 2021; Cucuzzella & Salvia, 2019). In this model, maintenance and post-consumer waste management are equally important. The use of virgin plastics should be replaced by post-consumer recycled polymers, such as recycled PP (rPP) or the well personally recycled PET (rPET) and other bio-based alternatives (polylactates, PLA, Polyhydroxyalkanoates PHA, or bio-polyamides). These substitutes lead to improvements on the reduction of greenhouse gases and resource use (Bovea *et al.*, 2020; Parente *et al.*, 2022). However, the substitute materials must be weighed against the required technological performance, (usually dishwasher) functionality, with consideration to mechanical strength, heat resistance and water stability (Meng *et al.*, 2024).

To manage this balance, designers and researchers are increasingly employing data-driven selection systems, such as Granta EduPack (or Selector). EduPack offers a selection of materials, and an extensive database that includes, technical and environmental data of thousands of materials, and facilitates a comparative analysis of materials based on sustainability criteria. (insert more analysis instead of data use to describe systems etc.). These are mainly embodied energy, CO₂-emissions, recyclability, and toxicity (Vakhitova, Shercliff, & Ashby, 2015; Granta Design, 2023). The use of such software early in the design process enables engineers to identify cost-effective combinations of materials that reach the outlined goals, which include performance and sustainability (Ferraresi & Del Curto, 2025).

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Thus, this study aims to identify how the ecological footprints of dishwashers can be reduced through the recycling, reusing, and thoughtful selection of materials. The focus of this study revolves around identifying substitute materials that fulfil their functional specifications with lower ecological impact. This research uses software and supporting scientific literature to perform comparative material analysis, providing suitable alternatives to the traditional components. The intention is to guide the appliance industry on environmentally preferable material options and support circular and sustainable manufacture of dishwashers.

1.1 The Company

Asko Company is one of the Swedish top household and professional appliances manufacturers. They have been recognized for product innovative design and product sustainability. Asko Company was originally established in 1950 in Sweden's Vara region. Nowadays, Asko Company serves over 120 countries with a diversified product range, which includes, dishwashers, refridgerators, washing machines and other small appliances for domestic use. Over the years, Asko Company has become one of the leading home Industry producers worldwide. (Asko AB Group 2023).

Asko AB is one of the first companies to develop and implement comprehensive sustainability strategies. They take pride in their sustainability strategies where they aim to reduce carbon emissions across for a 70% of their value chain in a sustained period and focus on recyclability and value in the design of every product and material (Asko AB Group 2023). Asko AB uses eco-design, responsible material sourcing and life cycle assessment as innovative strategies to reduce sustainability risks (Asko AB Group 2023).

Recently, Asko AB has made material innovation and data-driven design a priority, including the assessment of valued recycled plastics, bio-based polymers, and alternative metals for home appliances. This effort corresponds precisely with the focus of the current research, which aims to decrease the environmental impact of dishwashers through the sustainable selection, recycling, and reuse of materials. Asko AB's first-hand experience coupled with its openness on material sustainability offers, for this research, an ideal industrial reference (Ribeiro *et al.*, 2022).

Asko Appliances AB serves as a model of sustainable manufacturing. The company environmental management standards and applies design-for-disassembly principles, enabling easy repair, maintenance, and material recovery. By focusing on long product lifespan, energy efficiency, and recyclability, Asko demonstrates how sustainable design can reduce waste and resource consumption across a product's life cycle (Asko Appliances AB, 2023).

1.2 Problem Description

Household dishwashers perform a valuable service in modern household practices by saving water and energy compared to washing dishes by hand. Nonetheless, their disposal impacts the environment because of the materials and energy used to manufacture them, and the energies used to recycle and recover them at the end of their life (Fardente *et al.*, 2015). Most

of the dishwashers are made of non-renewable materials, mainly metals and fossil fuel plastics, and ABS and PP. These materials are produced in high quantities and are discarded with low recovery levels at end-of-life (Biganzoli *et al.*, 2016).

Complication in the materials and design of dishwashers pose a challenge. These include the heterogeneous clusters of materials, adhesives and coatings, and exotic materials in the electrical assemblies. Hence, plastic end-of-life components are a huge problem because of the additional complex stabilizers, flame retardants, and colorants (Nordahl *et al.*, 2024). Therefore, end-of-life dishwashers are incinerated and/or landfilled, contributing to greenhouse gases and toxic leachates (Hischier *et al.*, 2020).

The other most significant problem is the absence of sustainable alternatives for the materials used in the design of home appliances. Although recent research has validated the use of bio-based and recycled polymers in place of conventional plastics, their application is still restricted due to subpar mechanical and thermal performance (Parente *et al.*, 2022; Meng *et al.*, 2024). For this reason, manufacturers still lack fully non-toxic materials that are also sufficiently reliable. Research aimed at establishing substitute materials that reduce the dishwasher's environmental impact while still maintaining its functional parts is urgently needed.

This study seeks to explore some of the possible ways to mitigate the environmental effects of dishwashers by investigating the use of sustainable materials, recycling, and reuse. Our study aims to pinpoint the problem of switching out conventional, non-renewable materials with ones that are more sustainable and eco-friendly while still complying with the functionalities and operational parameters of the household appliances. The study aims to address the sustainability of materials from the life cycle perspective and, thus, is intended to advance the shift to a sustainable circular economy in the domestic home appliance sector (Matsumoto *et al.*, 2021; Cucuzzella & Salvia, 2019).

This project places particular attention on the use of data-based tools for the environmentally conscious and sustainable selection of materials, especially Granta EduPack (or Selector), as a novel scientific approach to the assessment and comparison of materials in their environmental and engineering parameters (Granta Design, 2014). The use of these tools data in product design encourages industry to take the leap from conventional, unsustainable plastics to recycled and bio-based plastics (Bovea *et al.*, 2020; Nordahl *et al.*, 2024).

Finally, the study intends to show that the sustainability of design extends beyond energy efficiency during use to include the sustainability of the design's constituent materials. This study will thus assist in the preparation of guidelines for sustainable dishwasher production and the enhancement of environmental policies (Ferraresi & Del Curto, 2025) through comparative analysis of recyclability, embodied energy, and CO₂ emissions.

1.3 Objectives

In order to achieve the goals, the following research objectives were articulated:

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- Identify the principal materials utilized in dishwashers and evaluate the resulting environmental impacts.
- Assess alternative recycled and bio-based materials using Granta EduPack and literature.
- Evaluate the mechanical, thermal, and environmental performance of conventional and suggested, more sustainable materials.
- Assess the impact of component recycling and reuse on the reduction of the total life-cycle footprint of dishwashers.
- Propose actionable guidelines on sustainable material selection and circular design principles for subsequent dishwasher production.

With these objectives, we hope to advance the practice of sustainable engineering in the dishwasher industry and help minimize adverse impact of materials on the environment.

1.4 Limitations

This study investigates the effect of the selection of materials, recycling, and reuse on the environment with regard to household dishwashers. It is limited to the analysis of the composition of materials that make up current dishwashers, and other life-cycle phases, such as the logistics of manufacturing, the consumer, and the energy efficiency of the dishwasher while in operation, are not covered in depth. Thus, the scope of this work is limited to the study of sustainability in materials that affect the design, the dishwasher's production, and end-of-life management.

The study assesses the use of recycled and bio-based polymers in place of conventional petroleum-based plastics and the value of designed integration of the circular economy (Matsumoto *et al.*, 2021). In this analysis, materials were compared in terms of mechanical, thermal, and environmental and other performance indicators with regard to recycling and sustainability as covered in the scientific literature, as well as the data in the Granta EduPack and Selector (Granta Design, 2014).

The impacts of selected materials will be analyzed mostly from the technical and ecological perspectives. The economic, social, and policy dimensions will be recognized in the value of the work but not elaborated. The findings will, therefore, aim to be the first step in interdisciplinary research in the area of sustainable engineering (Ferraresi & Del Curto, 2025).

The research cannot be considered complete in its understanding of the range of sustainable materials available for dishwashers. A first limitation in the material comparison is that it draws largely from secondary sources like published papers and the EduPack database instead of direct measurement in the laboratory, which means that material performance findings will depend on the quality and completeness of the existing databases (Al-Ezzi, Edan, & Anas, 2025).

Furthermore, proposed materials' practical implementation may be impacted by the geographical variability of production, different local recycling practices, and regional waste

management interventions. For example, the recyclability and embodied energy of a plastic material will be influenced by local waste management and polymer recycling techniques (Nordahl *et al.*, 2024). Limitations on time and costs were factors in the study and led to the analysis of only the primary components of dishwashers, this involved the internal plastic housings, racks, and pumps, and electronic and mechanical subsystems were not analyzed in depth (Biganzoli *et al.*, 2016).

In addition, the lack of large-scale economic analysis of consumer acceptance, industrial feasibility, and costs associated with this study, needs engagement with manufacturers and policy stakeholders to ascertain the practicality of these proposals. Notwithstanding these limitations the research offers clearly definable sustainable material principles which could be the basis for more design and experimental research and construction (Parente *et al.*, 2022).

2 Methodology

A comparative and analytical research strategy was employed to investigate materials that could be used to reduce the environmental impact of dishwashers. Sustainable materials research is mainly secondary data research. The author used various databases of material properties and peer reviewed literature in contrast to laboratory testing. In some sustainability research, as in this case, material data evaluation helps to discriminate which potentially sustainable substitute materials can be adopted when large-scale testing would not be viable (Ferraresi & Del Curto, 2025).

This study investigated the selection, appraisal, and comparison of materials for home dishwashers to replace plastic fossil-fuel-based materials with recyclable and bioplastics. The technical properties investigated were mechanical properties as well as the materials' resistance to heat and moisture. The environmental properties investigated were the energy and emissions represented in the material as well as recyclability (Nordahl *et al.*, 2024). The process involved three sequential steps.

The first stage was a literature review, with the goal of quantifying the main materials used in the production of dishwashers (Fardente *et al.*, 2015; Biganzoli *et al.*, 2016). Additionally, they used stainless steel, copper, aluminum, PP, and acrylonitrile butadiene styrene (ABS) as reference materials.

For material selection and comparison, materials were chosen in Granta EduPack by filtering on mechanical and thermal material parameters (e.g. tensile strength, tensile modulus, thermal stability), and environmental parameters (e.g. energy [MJ]/kg; emissions [kg CO₂/kg material]). EduPack selection charts were used to rank candidate materials and determine how well the performance criteria balanced against the various sustainability parameters.

The qualitative evaluation of the selected materials was made on the basis of the literature and databases. For comparison, the three categories were sustainable and conventional materials for:

1. Feasibility of performance (strength, durability, and thermal resistance)
2. Environmental advantage (represented energy/recyclability)
3. Adoption feasibility (availability, processing compatibility)

These three dimensions form the basis for the final analysis of materials that have the best trade-off between function and environment.

2.1 Comparative Material Assessment (CMA) Design

The approach of the study utilizes a component part level Comparative Material Assessment (CMA), whereby each individual part of the polymer based appliance (such as is PP compared with the bio-baseable polyhydroxyalkanoates and grades of polylactic acid. Due to the bottom up analytical framework the losses from the materials was enabled to be accounted for functionally (Ugural, A. C., 2020).

In this study, it is hoped that the substitution of original petroleum-based polymers for bio-based polymers like PHA or PLA will keep the original geometry of all the components the same after the substitution. This is helpful to isolate the non-geometric related effects of the materials used in relation to mass, density, environmental effects, functional performance.

To ensure that there was functional equivalence of both original and substituted materials, the mass of each component was recalibrated, virtually and inappropriately. The following formula was used:

$$m_{substituteis} = P_{substituteis} \times V_{component} \quad [\text{Eq 1}]$$

In this formula, $m_{substituteis}$ is the mass of the component made of substitute material, $P_{substituteis}$ is the density of the substitute material, and $V_{component}$ is the volume of the component.

In this way, all comparisons were adjusted to eliminate any size or shape variances, and in this regard, there was no non-geometric related substitute effect. As an example, consider a braided door hinge from POM with a component volume of 4.0 cm³. When it was substituted with PHA (density ≈ 1.24 g/cm³), the mass that was recalculated for it in relation to the density of the substituting material was added while other constitutive, geometric, and functional characteristics (Ugural, A. C. 2020; Dahiya, S. *et al.*, 2020).

This method helps identify other related effects, such as how much energy is used to manufacture them, or the possible changes in mechanical load distribution because of an increase in mass. By keeping the volume constant, the study also zeroes in on the effects of the specific material, which is an important factor in comparative sustainability assessments (Chen, 2023).

2.2 Evaluation of the Environmental Framework and Granta EduPack

Understanding the environmental impacts of material substitution is the most important aspect of this study. This framework offers a way to evaluate and quantify the most relevant

dimensions of energy use and carbon emissions, as these are considered the most important parameters of the environmental impact of the manufacturing of polymer-based components (Zanghelini *et al.* 2020).

Material selection is performed using a software package, typically Granta EduPack (also known as Granta Selector). EduPack for Universities is a version of Selector, a materials database that provides information on over 4,000 engineering materials. The database presents the physical, mechanical and environmental properties of engineering materials based on industrial averages and estimates of experimental data (Ashby 2017). It allows users to filter, compare and visualize materials in terms of a range of measurable sustainability and performance indicators.

EduPack provides data tables for represented energy, CO₂ emissions, recyclability, toxicity, resource-depletion and other aspects, and provides a strong choice support tool for the design of sustainable products (Granta Design, 2023). Coupled with life cycle thinking and technical performance data, the software can help users understand the performance of modern materials and customary plastics such as recycled (rPET, rPP), bioplastics such as PLA, PHA, and common polymers such as ABS and PP (Parente *et al.*, 2022).

2.3 Energy Consumption Assessment

Energy consumption is measured as primary cumulative energy demand in megajoule (MJ) and encompasses all the energy (upstream) involved in the production of a unit of material and its conversion into a functioning component. The following are important considerations:

1. **Material synthesis energy:** Energy involved in polymerization and compounding activities.
2. **Processing energy:** Energy involved in injection molding, extrusion, and other manufacturing activities.
3. **Energy normalization:** Energy values are normalized by functional unit so that valid comparisons can be made for materials or components regardless of dimensions or mass.

Recent studies highlight the importance of energy demand as a metric of sustainable because it correlates to the potential for carbon emissions, operational cost, and the overall impact to the environment (Pathak, P. *et al.*, 2023). PHA and high-heat PLA bio-based materials typically result in higher processing energy because of the thermal requirements, and yet because of the renewable feedstock the total environmental impact can be offset (Dahiya, S. *et al.*, 2020).

Energy consumption is measured in megajoules (MJ) and accounts for total primary energy as fully needed by the material (before any processing, including extraction, synthesis, and

manufacturing). The delta energy (ΔEnergy) of the original and substitute materials is determined as:

$$\Delta\text{Energy} = \text{Energy}_{\text{substitute}} - \text{Energy}_{\text{original}} \quad [\text{Eq 2}]$$

This kind of analysis can capture the balance of environmental sustainability and manufacturability. For example: PHA substitution for PP components increases mass, which slightly raises energy demand during injection molding. However, its renewable feedstock reduces upstream fossil energy consumption.

PLA substitution for ABS+polycarbonate (PC) may require additional energy due to thermal stabilization or flame retardant incorporation, but it eliminates the need for complex multi-polymer recycling processes, which are highly energy-intensive.

Environmental assessments are only as good as the energy analysis that accompanies them. Energy analysis integrates carbon footprint assessments and energy demand assessments. It considers the energy associated with the manufacture of an item, and the energy reduction benefits that item provides over its lifecycle. This aids the selection of materials in the design of sustainable appliances (Auras *et al.*, 2023; Koller *et al.*, 2023).

2.4 Carbon Footprint Evaluation

The calculation of the carbon footprint associated with each component uses CO₂ equivalent (CO₂e) emissions, which represent the total greenhouse gas (GHG) emissions in equivalents of kg CO₂. Such emissions are assessed in the cradle-to-gate context which includes the following processes:

1. **Extraction of raw materials:** Mining, collecting, or fermenting the feedstock.
2. **Polymerization:** Chemical processes that synthesize POM, PP, ABS+PC, PHA, and PLA, including polymerization of monomers, use of catalysts, and purification.
3. **Composite Processing:** Processing of each component, including, but not limited to, energy and emissions of injection molding and extrusion.

The emissions of CO₂ equivalents (CO₂e) are used to represent the global warming potential (GWP) of materials used in production. CO₂e represents the emissions in the cradle-to-gate context and includes the raw materials, the energy used in polymer synthesis, and processing.

This was calculated as:

$$\Delta\text{CO}_2\text{e} = \text{CO}_2\text{e}_{\text{substitute}} - \text{CO}_2\text{e}_{\text{original}} \quad [\text{Eq 3}]$$

This is to show the material substitution's environmental benefits or concerns. Replacing PP with PHA in the tip protection components could possibly increase the mass, but in the long-term, it decreases carbon emissions because it is renewable and biodegradable. On the other hand, replacing ABS+PC with PLA (high heat) could increase the CO₂e temporarily, because, due to the higher processing units, but if we analyze it in the context of the end-of-

life, the biodegradable factors of the processing could balance it (Sandanamamy, L. *et al*, 2023, Zhang *et al*, 2024).

This CO₂e evaluation is consistent with the state-of-the-art life cycle assessments (LCA) and is grounded to the most recent works on bio-based polymers (Dahiya, S. *et al*, 2020, Philip *et al*, 2022).

2.5 Data Sources and Validation

The database working as the basis of the research is taken from Granta EduPack 2023, literature published between the years 2015-2025 from peer-reviewed journals, and are verified with the two-source verification method. The database information also coheres with the published environmental studies which supports reliability (e.g. LCA studies by Fardente *et al.* (2015), Hischier *et al.* (2020)).

The author's approach on the data collection and calculations is with the intention to create, structured, and traceable methodology to evaluate the environmental and functional impacts of replacing conventional paper-based polymers with bio-based alternatives. The author's methodology focuses on the quantitative data and ensures that all evaluations are based on similar functional criteria and spatial parameters.

2.6 Ethical and Reliability Considerations

The study's use of secondary data and simulation software (rather than involving animals or humans directly) meant ethical approval was not needed in this case. Rigorous data sources (EduPack, European Commission JRC, peer-reviewed literature) and standardized criteria selection ensured reliable results that were within the limitations of the study's scope. These materials were compared according to the same properties and normalized data to allow comparison of materials to be made (Ashby M. F., 2022).

3 Background - Dishwasher Components

The last decade, in terms of domestic appliance and other domestic products design, has produced the least sustainable forms of industrial design and the least sustainable environmental policies in the world. The design and policies in question are that waste in the form of unsustainable disposable products. Policies for the design of household appliances have focused on reducing their energy consumption and recyclability of waste (Hischier *et al*, 2020). Among household appliances, dishwashers have historically been some of the most environmentally costly, due to the complexity in their materials and energy used over their life cycle (Fardente *et al.*, 2015).

3.1 Historic background to the material

Like other household appliances, dishwashers are made from a mix of materials, such as aluminum, copper, stainless steel and a high number of plastics, which are themselves high represented energy and environmental cost expensive (Biganzoli *et al.*, 2016). Plastics are used

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as they are unsustainable, having been made from mostly fossil fuels themselves, though are difficult to recycle due to their mixed plastic additives (Nordahl *et al.*, 2024). The environmental impact of Dishwashers is made worse when these materials are disposed of in landfills.

In recent years, some sectors have adopted circular economy and eco-design principles which revolve around products designed to be disassembled, repaired, reused and recycled (Matsumoto *et al.*, 2021; Cucuzzella & Salvia, 2019). These principles aim to extend product life, by reducing the demand for extraction of materials and energy. For example, dishwashers must adopt new, low impact recycling, reuse, and recycling strategies without compromising performance.

Recent studies and reports from the JRC of the European Commission indicate that 10-20% of the total environmental impact from the production and disposal of dishwashers, is from the materials used in the production of the dishwashers (Fardente *et al.*, 2015). Thus, the selection of materials impact in an environmentally responsible way is, and should be, an essential part of reducing the appliances' total life-cycle impact.

Improvements in data-centric materials engineering—specifically the use of software such as Granta EduPack (or Selector)—allows analysts and designers to assess and rank materials in relative function and environmental performance (Granta Design, 2014). This software provides a pathway for the selection of scientifically defensible sustainable substitutes for traditional plastics and metals, as well as for the recyclability, durability, and energy efficiency of dishwashers, which has been a focus of research and engineering.

The international sustainability agenda and the ambitions of the circular economy focus on recyclable and sustainable material alternatives to minimize the environmental impact of dishwashers throughout their life cycle. This project also seeks to contribute to this agenda in the context of the growing environmental impact of dishwashers.

3.2 Contemporary design

A dishwasher today comprises many parts that work in harmony with each other to clean the dishes (see Figure 1). The sink, usually made of stainless steel or other strong plastic material, is the middle bowl-like part that is insulated and where dishes are loaded for washing. These shelves help in dividing the dishes into portions during loading and help during the storage of clean dishes. Most dishwashers have an upper shelf for lightweight items like cups and mugs and a lower shelf for large dishes and utensils. There is also a third rack or silverware basket for utensils. The spray arms are the main components of the cleaning system. They are rotating assemblies that are located at the bottom, middle, and sometimes the top of the tub. Their function is to release hot, pressurized water through nozzles designed to remove food remnants at various angles. Circulation of water is done by a pump located beneath the tub with the help of a motor that forces water through the arms and maintains the pressure.

Parts of a dishwasher

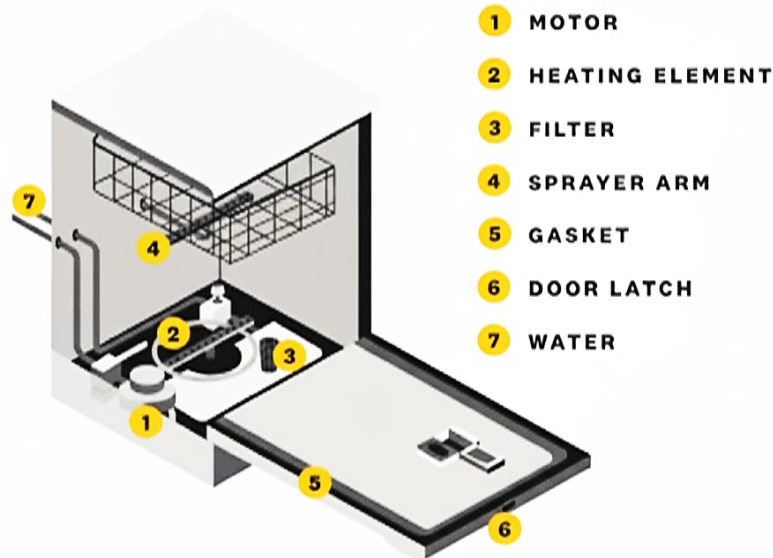


Figure 1 Diagram showing the labelled internal parts of a dishwasher (Asko)

The tub has a heating element which is a coiled metal that helps in two different ways during the washing and rinsing cycles. It raises the water's temperature to melt the grease, sterilize, and dry the dishes by warming the air to evaporate the water as they dry. Water management includes several components like an inlet water valve which regulates incoming fresh water, a drain pump to expel wastewater through the drain hose, and a pressure switch (or float valve) for detecting water levels while filling and draining. The filter system catches food residue at the drain and prevents it from going back onto clean dishes and clogging up the drainage system. It has a mesh filter and a fine filter that is positioned near the drain.

Control and operational functions are housed on the dashboard of the dishwasher. It contains electronic components, buttons, and digital displays that interact with users by showing washing programs and error codes as well as letting them choose the cycle. Other important components are the detergent and rinse aid dispensers that release cleaning agents at programmed intervals, the door latch that seals the door and activates safety interlocks so the machine cannot operate with the door open, the thermostat, and door gaskets that form a watertight seal on the door to contain water and prevent leaks (Fardente *et al.*, 2015).

Internals like housings, distribution racks, or pumps made from plastic are sustainability challenges since these are made from fossil resources, take a long time to degrade in landfills, and contaminated additives make them unrecyclable (Nordahl *et al.*, 2024). More than 99% of the raw materials used for plastic production and processing are fossil fuel based. Therefore, the production of plastics directly links to oil extraction and the long list of

environmental damages. The fossil fuel industry and the plastic industry are interlinked, especially since it is predicted that petrochemicals will constitute the largest portion of the growth for the global demand of oil in the next 7 years.

Plastic components used in dishwashers are made from a blend of additives to improve certain performance characteristics, such as durability, flexibility, heat resistance, and color. Performance characteristics are not the only reason for these additives, however. Stabilizers, plasticizers, flame retardants, and pigments are used to make them last longer, to provide ease of cleaning and to improve the aesthetic value of the device.

However, these additives present significant barriers to effective recycling, complicating material separation and contaminating recycling streams, sometimes reducing the quality of the resultant recycled plastics. About 80% of plastic additives impair the activity of the catalysts utilized in chemical processes of recycling, while some legacy additives, such as phthalates and brominated flame retardants, provide risks of toxicity that bar the utilization of recovered materials in consumer products. The heterogeneity within plastic waste streams, along with batch-to-batch variations in additive content, generates great technical and economical sustainability challenges to retrieve high-quality recycled material for reuse in exacting applications.

The selected dishwasher components were identified and documented during a field visit to the manufacturing facility, where the appliance was physically inspected. The inspection included visual identification, functional assessment, and on-site documentation of key structural and functional parts. A detailed description of these components, including their primary functions, is provided in *Appendix A (Table 1)* for reference.

3.3 End-of-Life scenario of dishwashers

At the end-of-life stage, the disposal of a dishwasher poses additional environmental concerns. If landfilled, improperly disposed dishwashers can leach toxic materials- heavy metals from wiring and solder, mercury from older control switches, and harmful chemical additives to plastics-into soil and groundwater. Parts made of plastic (that cannot be economically recycled) add to a landfill's burden and, if incinerated, contribute to the release of toxic chemicals to the air. Currently, only a small amount of materials from these appliances are recovered effectively; whereas most metal components in products, like stainless steel and copper, are often recovered, many plastic parts are not used again. The coating on the dishwasher racks, for example, is usually incinerated, while the metal frame is recovered. Roughly 60% of old dishwashers go into landfill sites, which is quite a waste of potential resources and adds up to increasing electronic waste concerns (Fardente *et al.*, 2015).

The present work focuses on the environmental impact of the dishwasher based on selecting sustainable materials, emphasizing reuse and recycling of components and the introduction of biobased polymers, recycled plastics in view of circular economy design.

4 Results And Discussion

A technical visit to Asko AB was conducted to obtain empirical data on the real materials used in manufacturing dishwasher components. A record of relevant components studied, with photos, is given in *Appendix A*. This fieldwork details the polymers incorporated in the firm's dishwasher components and maps them to the equivalent corresponding materials available in the Granta EduPack database for sustainability analysis. Several components, such as fixing brackets, base covers, door hinges, and control unit housings were dismantled and examined. For each component, the corresponding material code, SAP number, and tally quantity from the in-house inventory system are recorded. The materials encountered include various grades of conventional, petroleum-based polymers, such as polypropylene, that were investigated for replacement by biopolymers.

4.1 Company Data Collection Original Material Identification

The data presented in *Table 1* represents a combined outcome of academic material identification and field-based empirical verification. Component functions and material classifications are established through literature review and technical documentation, and subsequently validated through the technical visit to Asko AB, where actual components were inspected and matched with their corresponding industrial material grades. This integrated approach ensures that the scientific accuracy and the practical industrial relevance of the identified material baseline is preserved.

Table 1 Materials Identified During the Company Visit at Asko AB

Component Name	Volume [cm ³]	Material Type
Fixing bracket	6.0 cm ³	PP110
Fixing bracket	6.0 cm ³	PP110
Tip protection	136.1 cm ³	PP131
Base cover back	210.1 cm ³	PP131
Door hinge braided	4.0 cm ³	POM001
Coupling holder	15.6 cm ³	PP110
GCU holder	46.6 cm ³	PP123
Air break	370 cm ³	PP131
Water softener	419.7 cm ³	PP110
Float bracket	29.1 cm ³	PP 118
Spring Stretcher	13.1 cm ³	POM001
GCU-L housing	52.7 cm ³	ABS+PC
White plastic base	1680 cm ³	PP-T20

Thus, Table 1 is a baseline result that has been integrated and peer-reviewed and finally provides the reference result for the subsequent analyses of sustainability and material substitution.

The analysis encompasses thirteen representative functional plastic components, some of which are small, mechanically active components, (*e.g.* door hinge braided, spring stretcher) and some of which are larger, structural plastic housings (*e.g.* airbreak, water softener). The materials being researched include:

1. Polypropylene (PP – homopolymer, high flow) which is used in large quantities because of its great chemical resistance, low price, and ease of injection molding.
2. Polyoxymethylene (POM - copolymer) which has great stiffness, low friction, and excellent dimensional stability.
3. ABS+PC blends which are plastic materials that are well balanced in regard to impact resistance, heat resistance, and structural strength.

The materials that are suggested as substitutes are:

1. Polyhydroxyalkanoates (PHA) are polymers obtained through the biotechnical process of bacterial fermentation of sugars and lipids. It offers the possibility to use renewable feedstocks while reducing greenhouse gas emissions from polymers.
2. The grades of Polylactic acid (PLA) which are modified for impact and high heat resistance possess are bio-based polymers sourced from lactic acid fermentation and are characterized by high thermal resistance and mechanical strength comparable to ABS+PC (Sandanamamy, L. *et al.*, 2023).

4.2 Detailed Description of Original Materials

The primary materials are analyzed to understand the technical and environmental characteristics of the most widely used plastics in household appliance component production.

- **Polypropylene (PP)**

Polypropylene is a member of the thermoplastic polymer family. This family comes from petroleum feedstock. PP has low density. PP has chemical resistance. PP has good processability. These traits make it a common material in industry and consumer products (Klempner & Frisch, 2023). Related parts made of high flow homopolymer PP include the fixing brackets, tip protection, base covers, coupling holders, and structural housings, which benefit from high shape fidelity and good dimensional stability during injection molding.

Key physical and mechanical properties for PP are:

1. The density is low: 0.903 g/cm³ (0.033 lb/in³). This is useful in lightweight structures.

2. Good fatigue resistance: tolerates cycles of stress without breaking.
3. High degree of chemical stability: resistant to acids, bases and all but the most aggressive solvents.
4. Processability: Its injection moldability enables large numbers of parts to be produced with few defects.
5. Low material cost: Costs are relatively low compared to engineering polymers.
6. PP has several environmental disadvantages for consideration.
7. Because it is fossil-based, its producers emit greenhouse gases from and deplete non-renewable resources (Dahiya, S. *et al.*, 2020).
8. Plastic's low biodegradability results in its accumulation in landfills and natural environments (Peeke, L. M. *et al.*, 2024).
9. PP can be recycled, but this is often not cost-effective due to contamination and joining with other materials.

- **Polyoxymethylene (POM – Copolymer)**

Polyoxymethylene is an engineering thermoplastic with high mechanical performance and is frequently used in applications requiring precision and durability (Hassan *et al.*, 2023). The POM copolymer utilized in this study is selected for mechanically stressed components such as door hinge braids and spring stretchers due to its exceptional dimensional stability and stiffness.

Principal material characteristics:

1. The high stiffness and strength are ideal for components subjected to repetitive mechanical loads.
2. The low friction coefficient is ideal for moving parts with sliding contact.
3. The excellent dimensional stability and integrity is maintained over varying temperatures.
4. Density: 1.40 g/cm^3 . which is higher than the PP resulting in a higher mass for the same volume.

POM Relative environmental concerns include:

1. The polymer production process from which POM is made results in higher CO₂ emissions for the same mass than those posed by a simpler thermoplastic.
2. Pathak, P. *et al.*, 2023, mentions the high energy consumption during the extraction of the raw materials and polymerization.

3. Limited recyclability, which requires specialized mechanical or chemical systems, is not available for POM.
4. POM's mechanical traits will lend itself well to critical moving components, but its environmental impact should be weighed against potential POM substitutes that are bio-based.

- **ABS + PC Blend**

In terms of impact resistance and structural integrity, ABS+PC is an ideal candidate for housing components in household and electronic appliances. The blend consists of acrylonitrile-butadiene-styrene (ABS) and polycarbonate (PC) and is used in applications that require structural and impact resistance on Sandanamsamy *et al.*, (2023) and the ABS+PC blend is an ideal candidate for housing components in household and electronic appliances.

ABS+PC is an ideal candidate for enclosures and structural housings in applications where mechanical strength, dimensional stability and thermal endurance are the most critical.

The main material characteristics are:

1. Impact resistance: Absorb hits and are designed to sustain structural collapse, shakes, and are even mechanically adjustable to survive assemblies that encounter additional structural components.
2. Stability: Maintain dimensional and adjustable structures at designated operational assignment levels.
3. Precision: Facilitates operational ranges assignment structures at the defined limits.
4. Rigidity: Pure structural ABS does lend additional stiffness to the overall structure, but in comparison to pure ABS, the structure does lend additional stiffness to the overall structure.

Factors to consider when using ABS+PC include:

1. Production of complex polymers: Construction of ABS+PC necessitates a complicated and energy-consuming process that involves a myriad of chemical additives.
2. Excessive energy depletion: ABS+PC uses more energy than simple polymers.
3. Limited ability to be reused: Multi-polymer blends are complicated to separate when recycling and are often downcycled or thrown in a landfill (Zanghelini *et al.* 2020).

Although ABS+PC offers superior thermal and mechanical performance for demanding housing applications, its environmental footprint makes it suitable to be substituted for high-heat PLA or other more advanced bio-based high polymers.

4.3 Comparison at the Component Level

The CMA framework allows for the direct comparison of components at standardized geometric and functional boundaries. Hence, any difference in performance, energy use, or carbon footprint can be attributed to the material substitution rather than other design variables (Ugural, A. C. 2020; Dahiya, S. *et al.*, 2020). Each of the appliance components, as outlined in the original material table, is considered a distinct analytical unit. The environmental performance metrics are also included in the comparative framework (Zanghelini *et al.*, 2020).

Rather than assessing polymer materials in isolation, the study opts for a component-based approach, as the functional role, geometry, and mass distribution of each component affects material performance and the environment. The component-based approach guarantees that the recommendations for material substitution are specific to the application. For example, substituting a POM-based hinge with PHA cannot be justified by merely claiming a reduction in CO₂, as there may be compromises in fatigue resistance and dimensional stability after repeated load cycles (Ugural, A. C. 2020; Sandanamsamy, L. *et al.*, 2023). Using the defined functional unit, CO₂eq, component-specific energy performance indicators, and mechanical parameters (stiffness, density, impact resistance), and other performance metrics can be individually assessed or aggregated for a system-level evaluation.

4.4 Sustainable Design using Alternative Material in Appliance Manufacturing

More recent sustainable design frameworks increasingly emphasize eco-design principles, including recyclability, disassembly, and repairability (Ferraresi & Del Curto, 2025). This evolution illustrates a movement away from the simple substitution of materials and towards a sophisticated life-cycle approach to product development.

To facilitate eco-informed material selection, designers are increasingly using sustainability indicators, including embodied energy, carbon footprint, recyclability, and toxicity. These indicators are commonly provided by material selection databases, including Granta EduPack (Selector), which enable comparative evaluation of conventional and sustainable material alternatives (Ferraresi & Del Curto, 2025).

Functional performance is maintained when implementing recycled polymers, like recycled polypropylene and recycled polyethylene terephthalate into structural components of household appliances, as noted by Nordahl *et al.* (2024). With their use for the first time, the potential for incorporating recycled materials into components with a reduced environmental footprint while maintaining performance reliability was demonstrated.

At the same time, “green” polymers, such as polylactic acid and polyhydroxyalkanoates, also have advantages as renewable feedstock polymers with lower greenhouse gas emissions. However, current limitations with heat and moisture resistance have restricted their use in high temperature and high-performance applications (Meng *et al.*, 2024).

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- Household appliance life cycle assessment (LCA) reveals that the use phase, although largest in terms of energy usage, is still a noteworthy cause of environmental loading for material and end-of-life phases (Hischier *et al.*, 2020). Virgin polymer manufacturing, for example, is a major source of CO₂ emissions and consumption of non-renewable energy.
- European Commission Joint Research Centre (JRC) conducted a detailed LCA of dishwashers and arrived at the conclusion that 10–20% of total environmental effect is accounted for by materials, depending on recycling levels and efficiency of design (Fardente *et al.*, 2015).

It may seem advantageous to use alternatives to plastic, but several studies highlight anticipated rebound effects. In some cases, the use of bio-based alternatives may lead to increases in net greenhouse gas emissions owing to more greenhouse gas emissions from processing or from inputs to the agriculture used to grow the feedstock. Such cases reinforce the need to use evidence-based substitution in a more tailored approach compared to blanket substitution Meng *et al.* (2024).

4.5 Baseline Characterization

The original material data for the selected household appliance components (see Table 2) include polymer type, component volume, mass, density, carbon footprint (CO₂eq), and cumulative (embodied) energy. The dataset serves to establish the baseline performance of sustainable polymers compared to the petroleum-based polymers used in the comparative assessments.

Table 2 Original material dataset

Component name	Material type	Volume [cm ³]	Mass [g]	Density [g/cm ³]	Carbon footprint [kg CO ₂ eq]	Embodied Energy [MJ]
Door hinge braided	POM (Copolymer)	4.0	5.6	1.40	0.0178	0.48MJ
Fixing bracket	PP (homopolymer, high flow)	6.0	5.42	0.903	0.0127	0.42 MJ
Fixing bracket	PP (homopolymer, high flow)	6.0	5.42	0.903	0.0127	0.42 MJ
Tip protection	PP (homopolymer, high flow)	136.1	122.9	0.903	0.289	9.62 MJ
Base cover back	PP (homopolymer, high flow)	210.1	189.7	0.903 ³	0.446	14.85 MJ
Coupling holder	PP (homopolymer, high flow)	15.6	14.1	0.903	0.0331	1.10 MJ

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GCU holder	PP (homopolymer, high flow)	46.6	42.08	0.903	0.0989	3.29 MJ
Air break birton	PP (homopolymer, high flow)	370	330	0.903	0,78	26 MJ
Water softener	PP (homopolymer, high flow)	419.7	380	0.903	0,89	29.7 MJ
Float bracket	PP (flame retarded V-0)	29.1	31.2	1.071	0.091	2,63 MJ
Spring Stretcher	POM (Copolymer)	13.1	18.3	1.40	0.0587	1.58 MJ
GCU-L housing	ABS+PC (injection molding and extrusion)	52.7	58.5	1.11	0.284	6.52 MJ
White plastic base	PP (copolymer 20% talc)	1680	1772	1.055	5.1	111

The statistical data in the Table 1-2 illustrates for each selected dishwasher component, the constituent parts, overall volume and mass, and environmental repartition on the materials proposed. Polyoxymethylene (POM – copolymer) is used, for example, in small mechanically active construction parts, such as door hinge braids and spring stretchers (Ugural, A. C. 2020; Dahiya, S. *et al.*, 2020). Although small in volume, these constituents hold higher density, specific energy and carbon footprints than the other constituents made out of polypropylene, thus reflecting higher material intensity of engineering thermoplastics (Pathak, P. *et al.*, 2023).

On the other hand, the primary structural as well as the housing constituents such as the base cover, the air break, the water softener and the white plastic base, are predominantly made of polypropylene (PP). The density of polypropylene (PP) being low, close to 0.903 g/cm³, makes it possible to have a mass-specific environmental impact that is lower relative to the rest of the mass of the constituents, but in spite of these base cover, air break, water softener, and white plastic base constituents having a low density, the volume of these makes them the highest contributor to the total energy of the cover and the carbon footprint of the rest (Sandanamamy, L. *et al.*, 2023). The polypropylene copolymer, 20% Talc-filled, is a polypropylene that has been chemically modified to a structural composite thermoplastic, with high performance to be used in structural applications (Pathak, P. *et al.*, 2023).

The GCU-L housing ABS+PC blend exemplifies a higher carbon footprint for its volume, illustrating the environmental disadvane associated with multi-polymer blends with high process energy. Based on the information collected regarding alternative materials and their potential to replace conventional materials, two main categories are taken into consideration in this study. In general, Table 2 shows possible relations between the three variables, i.e., type of polymer, design of components, and selection of materials, to the dishwasher's

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environmental impact, as far as the current document informs us to support further substitution and comparison studies (Pathak, P. *et al*, 2023).

4.6 Substitute Materials Dataset

The substitute materials dataset proposes sustainable bio-based polymers as alternatives to the original petroleum-derived materials. Specifically:

Recently, Sandanamsamy *et al.*, 2023, and Dahiya *et al.*, 2020, have reported PHA as a potential substitute for polypropylene (PP) and polyoxymethylene (POM) in specific applications. PHA is fully bio-based, and biodegradable, and is produced through microbially mediated soft-thermoplastic fermentation utilizing renewable feedstock. PHA has a reasonable rigidity, and thermal resistance; and can fit small to medium size components. Additionally, it can significantly lower carbon footprint compared to conventional fossil-fuel based thermoplastics.

For the housing components, ABS+PC can be replaced by Polylactic Acid (PLA) – High Heat. This specific type of PLA can perform at higher temperature and it provides comparable mechanical properties to the PLA, and, blends, of the previously used polymers. Furthermore, as a result of being of fully renewable feedstock PLA has, a lower carbon footprint, and is industrially compostable. However, the mechanical properties and performance of PLA need to be assessed for the specific conditions under prolonged loading (Pathak, P. *et al*, 2023) .

In Table 3, the substituted materials have their respective delta values ($\Delta\text{CO}_2\text{eq}$ and ΔEnergy) which can be used to estimate the environmental benefits directly from the material substitution. These values are the potential decreases in Greenhouse Gas (GHG) emissions and energy use. This is particularly important when choosing materials and designing for sustainability in the appliances. (Ugural, A. C. 2020; Sandanamsamy, L. *et al.*, 2023; Dahiya, S. *et al.*, 2020).

Table 3 Substitute material

Component name	Proposed substitute	Volume [cm ³]	Mass [g]	Density [g/cm ³]	$\Delta\text{Carbon footprint}$ [kg CO ₂ eq]	$\Delta\text{Embodied Energy}$ [MJ]
Door hinge braided	PHA	4.0	4.96	1.24	4.46	0.42
Fixing bracket	PHA	6.0	7.44	1.24	6.70	0.64
Fixing bracket	PHA	6.0	7.44	1.24	6.70	0.64
Tip protection	PHA	136.1	168.8	1.24	152	14.43
Base cover back	PHA	210.1	260.5	1.24	234	22.27

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Coupling holder	PHA	15.6	19.34	1.24	17.4	1.65
GCU holder	PHA	46.6	57.78	1.24	52.0	4.94
Air break bitron	PHA	370	459	1.24	410	39.3
Water softener	PHA	419.7	520	1.24	470	44.5
Float bracket	PHA	29.1	36.1	1.24	32	3.09
Spring Stretcher	PHA	13.1	16.2	1.24	14.6	1.39
GCU-L housing	PLA (high heat)	52.7	71.4	1.355	204	3.86
White plastic base	PHA	1680	2083	1.24	1.88	178

Using the information as a basis, initial comparisons in Granta EduPack were made, matching polymers with engineering materials, for example, Generic Polypropylene, Recycled PP, and Bio-based PP. Assessing these products in terms of mechanical strength, embodied energy, CO₂ eq emissions and recyclability, made it possible to ascertain which of the alternative recycled or bio-based materials could be used with a reduction in the environmental footprint for the trade-off of underproducing performance (Parente *et al.*, 2022; Nordahl *et al.*, 2024).

The dataset involving substitute materials suggests that bio-based polymers are more sustainable and offer the potential to meet the specified design objectives and, at the same time, minimizing the environmental impact of the components used in household appliances. Accordingly, the study thus narrowed down the materials in question to bio-based and biodegradable polymers, as a significant portion of both of these polymer categories is sub-classified as polyhydroxyalkanoates and polylactic acid. The study considered a range of specific attributes for each of these materials, including the source or origin, mechanical attributes, processability, functional performance, and environmental impact.

The figure shows the comparison of components on the basis of polypropylene (PP) and the two other components, polyhydroxyalkanoates (PHA) and polylactic acid (PLA), respectively. The figure shows the comparison on the basis of density, forecasted mass, and CO₂ equivalent emissions ($\Delta\text{CO}_2\text{eq}$) and shows the energy demand (ΔEnergy). Table 4 depicts the environmental impact of substituting a bio-based polymer for a fossil-derived polymer within a household appliance, as noted in the section.

The results in Tables 4-7 are comparative and are based on the methodology of selection and substitution of materials used in this study. Granta EduPack was used to compare conventionally manufactured polymers (PP, PP 20% talc, POM, ABS + PC) with bio-based polymers made from PHA and PLA.

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Values for mechanical properties (tensile strength, stiffness and impact resistance), physical properties (density) and environmental properties (represented energy and represented CO₂ equivalent emissions) were obtained from the EduPack database as well as using peer-reviewed literature sources.

Component-level mass was then recalculated by maintaining constant component volume and material density for functional equivalency, and environmental performance indicators ($\Delta\text{CO}_2\text{eq}$ and ΔEnergy) were determined by comparing the bio-based variants against their petroleum-based counterparts.

Thus, by using a multi-criteria decision-making method that incorporates mechanical performance, environmental impact, and manufacturability, the following discussion is targeted at the methodology as opposed to isolated qualitative considerations.

Material Comparison of PP, PHA, and PLA

Table 4 Comparison between PP/ PP20% talc/ PHA/PLA

	PP (homopolymer, flame retarded V-0)	PP (homopolymer, high flow)	PP (copolymer, 20% talc)	PHA (unfilled)	PLA (flame retarded)
Composition overview					
Base material	PP (Polypropylene)	PP (Polypropylene)	PP (Polypropylene)	PHA (Polyhydroxyalkanoates)	PLA (Polylactic acid / polylactide)
Additive	Flame retardant	None	None	None	Flame retardant
Renewable content (%)	0	0	0	100 ↑	85 - 95 ↑
Price					
Price (USD/kg)	2.21 - 2.61	1.12 - 1.47 ↓	1.71 - 1.94 ↓	3.85 - 5 ↑	3.62 - 4.22 ↑
Price per unit volume (USD/m ³)	2170 - 3020	1010 - 1340 ↓	1760 - 2090 ↓	4740 - 6250 ↑	4740 - 5530 ↑
Physical properties					
Density (kg/m ³)	982 - 1160	898 - 908 ↓	1030 - 1080	1230 - 1250 ↑	1310 ↑
Mechanical properties					
Young's modulus (GPa)	1.5 - 2.08	1.37 - 1.58	1.49 - 2.19	3.5 - 4 ↑	3.1 - 3.79 ↑
Yield strength (elastic limit) (MPa)	23.7 - 31.5	31.9 - 36.4 ↑	22.4 - 27.8	35 - 40 ↑	48.3 ↑
Tensile strength (MPa)	34 - 36	26 - 50	22.4 - 27.8 ↓	35 - 40	48.3 ↑
Elongation (% strain)	25.8 - 70.5	52.1 - 232	19.9 - 56.6	6 - 25 ↓	18 - 20 ↓
Impact & fracture properties					
Impact strength, notched 23 °C (kJ/m ²)	2.34 - 3.28	2.26 - 3.17	5.03 - 7.24 ↑	0.73 - 1.87 ↓	11.8 - 12.7 ↑
Thermal properties					
Melting point (°C)	161 - 170	161 - 170	145 - 176	171 - 182 ↑	135 - 181
Heat deflection temperature 1.8MPa (°C)	53.9 - 70	50.5 - 66.9	54.3 - 70.9	87 - 98 ↑	48 - 55
Maximum service temperature (°C)	80.6 - 103	95.1 - 114	77.1 - 94.8	60 - 80 ↓	40 - 60 ↓
Environmental indicators - material production					
Climate change (CO ₂ -eq) (virgin grade production) (kg/kg)	2.79 - 3.07	2.25 - 2.49 ↓	2.73 - 3.01	0.856 - 0.944 ↓	2.72 - 2.99
Embodied energy (virgin grade production) (MJ/kg)	80.1 - 88.3	75.1 - 82.8	59.9 - 66 ↓	81.3 - 89.7	51.4 - 56.6 ↓

Polyhydroxyalkanoates

- Advantages of PHA over PP:

As can be in Table 4, PHA's mechanical properties are similar to those of PP, with comparable tensile strength and stiffness. It can therefore be used for mechanically stressed articles such as clips, brackets and non-visible internal components. The full biodegradability of PHA in natural environments is another advantage over PP, which can result in persistent

plastic waste that can survive in the surroundings for many years (Koller *et al.*, 2023). PHA also has good resistance to chemicals, making it suitable for products exposed to detergents or water. PHA has a lower long-term environmental impact, which is due to a lower potential for microplastic pollution and a lower reliance on fossil carbon (Philip *et al.*, 2022).

- Limitations of PHA compared to PP:

PHA is denser than PP, meaning identical components would weigh more, which may impact energy efficiency during transport or use. PHA also has a lower thermal degradation temperature than PP, which may limit the processing temperature or alter the decomposition temperature of the plastic. This in addition to stringent temperature control and high production costs could drive up the cost of PHA production. Currently, PHA is much more expensive than PP due to low-scale production and highly complex fermentation processes relative to PP, making PHA impractical for items in a typical household or office (Li *et al.*, 2023).

Polylactic Acid (PLA)

Polylactic acid (PLA) is a type of thermoplastic aliphatic polyester made primarily from renewable and biodegradable materials such as corn, sugarcane, and other carbohydrate rich biomasses (Sandanamamy, L. *et al.*, 2023).

- Advantages of PLA over PP:

in the form of PLA, presents a more eco-friendly solution to PP, the costs associated with PHA production are significantly higher than those associated with PLA. The production of PLA is more advanced and provides for more economical production than PHA. Moreover, PLA grades such as high-impact and high-heat (see Table 5) can compete with PHA on performance and can substitute for PP in non-load-bearing and semi-structural components, appliance housing, and covers, etc. Furthermore, PLA is made from renewable resources, and typically has lower greenhouse gas emissions than the polymers made from fossil energy (Auras *et al.*, 2023).

- Limitations of PLA compared to PP:

Compared to PP, PLA has lower thermal and impact stability. Unless a high-performance grade is used, it is not appropriate for parts with high and/or continuous exposure to heat and/or mechanical impact. PLA, though mostly compostable, has less favorable end-of-life properties than fully biodegradable PHA, as it is compatible with industrial composting only. Also, PLA is denser than PP, so it may require more material to print a part (Auras *et al.*, 2023).

- PHA is superior to PLA as a PP substitute.

Naturally, PHA has higher biodegradability and mechanochemical similarity to PP, at least in the bulk level, but a much higher cost.

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PLA, while less environmentally robust in terms of biodegradation, provides a more cost-effective and commercially viable option for partial substitution, particularly in components with lower mechanical and thermal demands. Consequently, PLA is more suitable for large-scale, cost-sensitive applications, whereas PHA is better positioned for high-value components where environmental performance is prioritized over material cost (Philip *et al.*, 2022; Dahiya, S. *et al.*, 2020).

Table 5 Short Comparison between PLA (high heat), PLA (high impact), PLA (flame retarded)

	PLA (high heat)	PLA (high impact)	PLA (flame retarded)
Price			
Price (USD/kg)	2.61 - 3.18	3.16 - 3.67	3.62 - 4.22 ↑
Price per unit volume (USD/m ³)	3240 - 4670	3730 - 4590	4740 - 5530 ↑
Physical properties			
Density (kg/m ³)	1240 - 1470	1180 - 1250	1310
Mechanical properties			
Young's modulus (GPa)	3 - 4.9	2.28 - 4.3	3.1 - 3.79
Tensile strength (MPa)	40 - 60	37.9 - 48.1	48.3
Impact strength, notched 23 °C (kJ/m ²)	1.57 - 8.2	14 - 62.7 ↑	11.8 - 12.7 ↑
Heat deflection temperature 1.8MPa (°C)	90 - 113	49 - 50 ↓	48 - 55 ↓
Environmental indicators - material production			
Climate change (CO ₂ -eq) (virgin grade production) (kg/kg)	2.72 - 2.99	2.72 - 2.99	2.72 - 2.99

PLA (High Heat)

1. Engineered for applications requiring enhanced thermal resistance, capable of withstanding elevated temperatures without deformation.
2. Suitable for structural housings, components exposed to appliance operating heat, or near heating elements.
3. Offers moderate mechanical strength, making it compatible with light-to-moderate mechanical loads (Auras *et al.*, 2023).

PLA (High Impact)

1. Modified through copolymerization or blending with impact modifiers to increase toughness and resistance to sudden mechanical shocks.
2. Functions as a partial replacement for ABS+PC in housings where drop resistance and dimensional stability are critical.
3. Provides a good compromise between eco-friendliness and mechanical consistency, with a modestly higher density than standard ABS (Zanghelini, *et al.* (2020)).

PLA (Flame Retarded)

1. Designed to comply with fire safety standards, particularly relevant for electrical appliances and components with heat exposure.
2. Fulfills fire resistance requirements, along with a retention of biodegradability and processability.
3. When electrical insulation and safety standards need to be met, it is appropriate for covers or housings (Zhang *et al.*, 2024).

The three grades of PLA have differing pros and cons, given the specific needs of an application. For instance, high-heat PLA has increased thermal resistance but decreased impact strength (*i.e.*, brittleness), whereas high-impact PLA has greater toughness but lower heat resistance. Flame-retarded PLA, on the other hand, has the added benefit of meeting fire safety standards, but may come with increased cost and density, along with slight reductions in mechanical performance. As a result, the selection of a specific grade of PLA is a matter of compromise. For example, selecting high-impact PLA would tend to limit choices to mechanical reliability and safety.

Polyhydroxyalkanoates are a diverse family of microbially synthesized polyesters obtained from renewable feedstocks such as sugar, vegetable oils, and agricultural residues (Chen, 2023). PHA is proposed as a substitute for both polypropylene and polyoxymethylene in components where mechanical performance, chemical resistance, and environmental sustainability are key considerations.

POM copolymer is widely used in components with a high degree of mechanical movement, due to its high rigidity, dimensional stability and wear resistance. Potential equivalents to POM considered in (Table 6) are PLA variants, which present both advantages and drawbacks. Relative to standard PLA, high-heat PLA has a greater thermal stability and can be used in semi-static parts that have moderate temperature exposure; however, POM, in contrast to high-heat PLA, has greater fatigue resistance and mechanical strength.

High-impact and impact-modified PLA grades have a greater toughness and lower brittleness allowing their use in applications of intermittent mechanical loading. However, POM, in contrast to high-impact and impact-modified PLA, has lower friction and greater resistance to wear over time. When comparing POM and PLA, PLA has a lower carbon footprint and lesser energy and PLA does have a greater density and lower mechanical durability. Therefore, PLA is a partial replacement of POM in low to moderate applications, while POM is optimal in high reliance applications (Dahiya, S. *et al.*, 2020; Zanghelini *et al.*, 2020).

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Table 6 Comparison between POM/PLA (high heat, high impact) PLA (impact modified)

	POM (copolymer)	PLA (high heat, high impact)	PLA (impact modified)
Composition overview			
Base material	POM(co) (Polyoxymethylene / acetal copolymer)	PLA (Polylactic acid / polylactide)	PLA (Polylactic acid / polylactide)
Additive	None	Impact modifier	Impact modifier
Renewable content (%)	0	85 - 95 ↑	85 - 95 ↑
Price			
Price (USD/kg)	1.7 - 1.79	3.2 - 3.75 ↑	3.2 - 3.75 ↑
Price per unit volume (USD/m ³)	2360 - 2520	3900 - 4610 ↑	3900 - 4690 ↑
Physical properties			
Density (kg/m ³)	1390 - 1410	1220 - 1230 ↓	1220 - 1250 ↓
Mechanical properties			
Young's modulus (GPa)	2.6 - 3.2	3.1 - 3.4	2.37 - 3.6
Yield strength (elastic limit) (MPa)	53 - 68	50.6 - 67.6	42 - 72
Tensile strength (MPa)	71.5 - 89.6	50.6 - 67.6 ↓	42 - 72
Elongation (% strain)	15 - 75	4.1 - 7.8 ↓	5.8 - 200
Impact & fracture properties			
Impact strength, notched 23 °C (kJ/m ²)	4.14 - 7.51	9.4 - 19 ↑	2.3 - 7.84
Thermal properties			
Melting point (°C)	160 - 175	178 - 180 ↑	170
Heat deflection temperature 1.8MPa (°C)	85 - 121	90 - 113	49 - 50 ↓
Maximum service temperature (°C)	83 - 97	55 - 80 ↓	40 - 60 ↓
Environmental indicators - material production			
Climate change (CO ₂ -eq) (virgin grade production) (kg/kg)	3.04 - 3.36	2.72 - 2.99 ↓	2.72 - 2.99 ↓
Embodied energy (virgin grade production) (MJ/kg)	81.8 - 90.2	51.4 - 56.6 ↓	51.4 - 56.6 ↓

Material Comparison of ABS+PC (Injection molding and extrusion), PLA (High Heat) and PLA (High Impact)

ABS+PC and high heat and high impact grade PLA show tradeoffs in mechanicals, thermal resistance, and environmental impacts, making these comparisons valuable. In comparison, high heat PLA's thermal resistance is best, followed by high impact PLA, although this is an inadequate thermal resistance in comparison to ABS+PC, limiting these materials to lower heated components. High impact PLA also improves toughness and shock resistance and is thermally better, however it does not satisfy high temperature applications. In both cases, higher environmental impacts correlate with lower mechanical robustness and inadequate long term structural durability. Moderate grades and high impact grade PLA have a higher defensible position than ABS PLUS PC in terms of energy demand and CO₂ emissions. Overall, ABS+PC remains superior for high-performance housing components, while PLA variants serve as more sustainable alternatives for less demanding applications, depending on whether thermal stability or impact resistance is prioritized.

Table 7 Comparison between ABS+PC /PLA (high heat),PLA (high impact)

	ABS+PC (injection molding and extrusion)	PLA (high heat)	PLA (high impact)
Composition overview			
Base material	ABS+PC (Acrylonitrile butadiene styrene + polycarbonate blend)	PLA (Polylactic acid / polylactide)	PLA (Polylactic acid / polylactide)
Additive	None	None	Impact modifier
Renewable content (%)	0	100 ↑	80 - 85 ↑
Price			
Price (USD/kg)	2.71 - 2.85	2.61 - 3.18	3.16 - 3.67 ↑
Price per unit volume (USD/m ³)	2900 - 3280	3240 - 4670	3730 - 4590 ↑
Physical properties			
Density (kg/m ³)	1070 - 1150	1240 - 1470 ↑	1180 - 1250 ↑
Mechanical properties			
Young's modulus (GPa)	2.41 - 2.62	3 - 4.9 ↑	2.28 - 4.3
Yield strength (elastic limit) (MPa)	45 - 55	40 - 60	37.9 - 48.1
Tensile strength (MPa)	40 - 51	40 - 60	37.9 - 48.1
Elongation (% strain)	50 - 125	1 - 17 ↓	18 - 20 ↓
Impact & fracture properties			
Impact strength, notched 23 °C (kJ/m ²)	24.4 - 48.3	1.57 - 8.2 ↓	14 - 62.7
Thermal properties			
Melting point (°C)		170 - 180	179 - 180
Heat deflection temperature 1.8MPa (°C)	99 - 116	90 - 113	49 - 50 ↓
Maximum service temperature (°C)	63 - 77	55 - 80	40 - 60 ↓
Environmental indicators - material production			
Climate change (CO ₂ -eq) (virgin grade production) (kg/kg)	4.62 - 5.09	2.72 - 2.99 ↓	2.72 - 2.99 ↓
Embodied energy (virgin grade production) (MJ/kg)	106 - 117	51.4 - 56.6 ↓	51.4 - 56.6 ↓

4.7 Analysis of Comparisons

Fardente *et al.* (2015), Biganzoli *et al.* (2016), and Ardente & Mathieux (2014), for example, have focused on dishwashers, providing studies on dishwashers recyclability, material efficiency, eco-design, and impact studies. Together with appliance studies, they build a strong case that, to a reasonable extent, sustainable material substitution, circular design, and recycling optimization can be achieved, and that for dishwashers, this will greatly reduce waste and emissions across all life-cycle stages. There have been studies on the environmental performance and material efficiency of household appliances, but dishwashers have received very little of this attention.

Important life cycle and material flow analyses on dishwashers have been done by Ardente and Mathieux (2014) and, Biganzoli *et al.* (2016) and Fardente *et al.* (2015), but these primarily focused on energy use and recyclability, which did not provide a comparative analysis on the sustainable alternatives that can be materialized. Also, while the eco-design and sustainable materials research done in appliances (e.g. Bovea *et al.* 2020; Matsumoto *et al.* 2021; Parente *et al.* 2022) certainly aids the understanding of the integration of the circular economy, it still lacks a component level, practical substitution of dishwashers heated parts and materials, moist, and expose to chemical detergents. This gap lends itself to extensive analytical work that integrates material sustainability assessments with functional performance expectations for dishwashers.

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The current work begins to fill this gap by comparatively assessing the use recycled and bio-based alternatives to conventional materials, supported by tools like Granta EduPack. This work furthers the integration of circular and sustainable material strategies into the manufacturing of dishwashers by connecting environmental metrics - embodied energy, CO₂-footprint, recyclability to performance engineering. Future studies should conduct a detailed Life Cycle Costing (LCC) to confirm the economic feasibility, noting that PLA is generally cheaper than PHA in the current market.

As the materials chosen for the dishwasher components are evaluated for both environmental and functional performance, the results are clear. Structural components are mostly polypropylene because it is very cheap and has a lower density than others. However, the large volumes required for the construction of dishwashers mean that it contributes significant amounts of CO₂ to the carbon footprint. POM and ABS+PC (engineering polymers) are more expensive, and have more CO₂ as well as embodied energies, but they do have better heat and mechanical properties. Of all the materials evaluated, PHA and PLA biopolymers engineered for a particular purpose have the least overall impact. However, as biopolymers, they are weak structurally and have poor impact resistance. These outcomes lead to the conclusion that, for more sustainable products, it is more effective to do a more significant material replacement for a component than try to do a complete material conversion for the entire product.

The scatter plot in Figure 2, below, shows the relationship between embodied energy and climate impact (CO₂eq) of different plastic materials utilized in consumer appliances. POM and ABS+PC as typical polymers show high embodied energy and high CO₂ emissions per kg in virgin production. PP grades show reduced energy and emissions with talc-filled PP providing some further reduction of the negative impact. PHA of the bio-based options shows the lowest climate impact, while the embodied energy is moderate. PLA grades typically show intermediate values with a lower carbon footprint than POM and ABS+PC, but somewhat higher than PP while being of moderate energy demand. The plot shows the selection of bio-based polymers of PHA and PLA shows significant lower GHG emissions than high-performance engineering plastics and justifies the optimal use of materials for increased sustainability. One of the clearly defined and highly effective best practices for the household appliance manufacturing industry is the recycling of the appliance components. The results of this study suggest that recycling the conventional plastics is a more feasible and effective practice comparing to the complete substitution with bio-based plastics in the considered timeframe and scope. Recycled plastics, especially rPP, present mechanical and thermal properties similar to dishwasher components while offering meaningful reductions in represented energy and CO₂ emissions compared to virgin materials.

Additional advantages are the compatibility of recycled materials with the existing industry and their intrinsic properties, like avoiding the need for major redesign, reprocess, and re-qualification. Recycling also avoids the rebound effects that are commonly associated with bio-based plastics, including the occupation of land for agrarian industry, high energy consumption for reprocessing and related supply chain disruptions. Bio-based polymers are

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suitable for some niche applications of relatively low mechanical stress. However, recycling directly contributes to the goals of circular economy as it extends the lifetime of the materials, reduces fossil mechanical energy requirements, avoids landfill disposal and reduces the overall environmental burdens. Recycling is therefore the most viable, scalable and reasonable pathway for the sustainability of dishwasher component production.

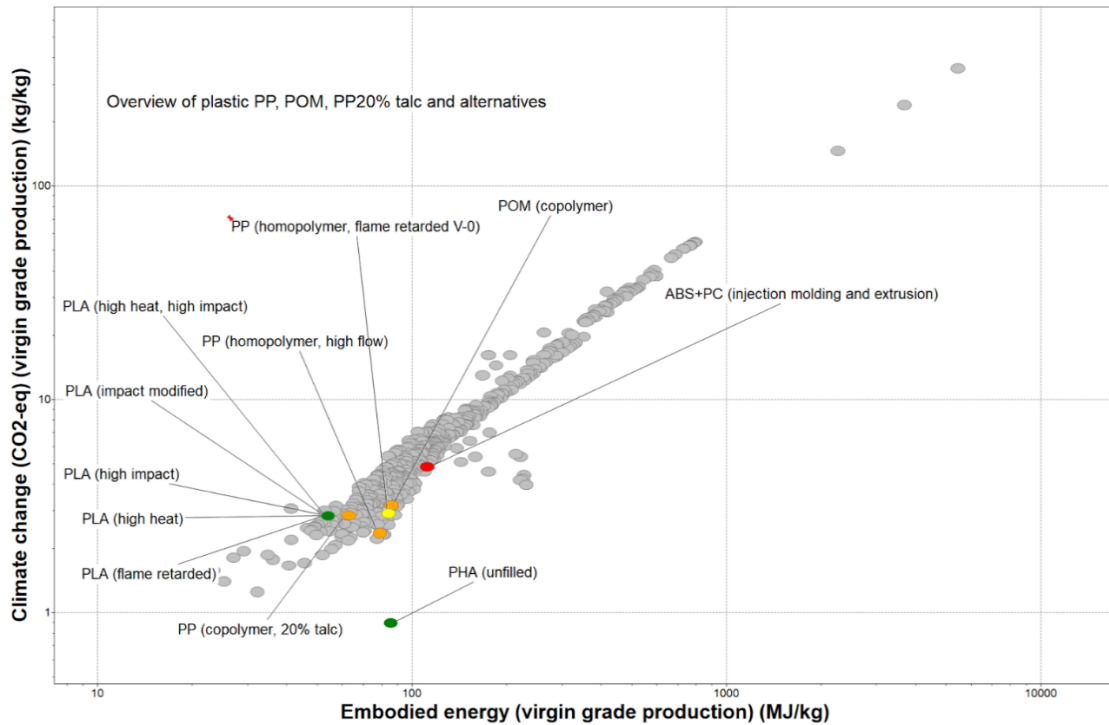


Figure 2 Comparison of different plastics (PP, PLA, POM, ABS+PC, PHA) in terms of embodied energy and climate impact

4.8 Conclusion

The findings in this study show that PHA and PLA as bio-based polymers represent a lessening of the environmental burden of the components of household appliances when considering the functional requirements. Some performance limitations exist, but the necessary polymers present for biopolymer PHA and PLA substitution will demonstrate significant reductions in carbon and other energy savings. This promotes the use of component-level approaches to define dishwasher designs of the future.

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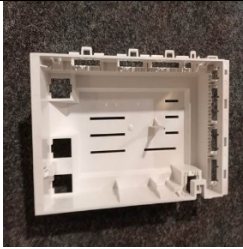
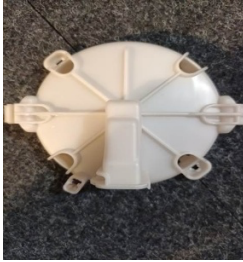


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Appendix A: Supplementary Data and Literature Review

Table A.1: Visual Identification and Functional Description of Selected Dishwasher Components

This table maps the identified components from Asko Appliances AB to their primary functions and provides a placeholder for visual documentation.

Component Name	Functional Description	Reference Image
GCU-L Housing	Protects and encloses the electronic control unit from moisture, heat, and mechanical damage.	
Float Bracket	Supports the float mechanism used to monitor and control the water level inside the dishwasher.	
Air break	Regulates and separates the incoming water flow, preventing backflow and protecting the dishwasher from overpressure and contamination.	
Water Softner	Reduces water hardness to prevent scale formation and improve washing efficiency.	

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Base cover	Provides structural protection to the bottom components and prevents water leakage.	
GCU-L holder	Supports and fixes the GCU-L housing in position, ensuring stability of the control unit during operation and vibration.	
Coupling holder	Secures hose and pipe connections to ensure proper water flow and mechanical stability.	
Fixing bracket	Holds and stabilizes internal components during operation and vibration	
Tip protection	Prevents appliance tipping and enhances user safety during operation	
Door hinge braided.	Facilitates smooth door movement and supports controlled opening and closing	
Spring Stretchar	Adjusts and maintains the tension of the door springs to balance the door's weight, ensuring smooth opening and preventing it from falling abruptly.	

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White plastic base	Provides a structural base for mounting and supporting internal dishwasher components, while offering insulation and protection against moisture and vibration	
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Table A.2: Summary of Previous Literature and Research Relevance

Comprehensive overview of key studies informing the current research on material substitution and dishwasher sustainability.

Author(s) / Year	Study Type / Methodology	Research Focus	Key Findings	Relevance to Current Study
Fardente et al. (2015)	Life Cycle Assessment (LCA)	Environmental footprint of dishwasher production and material efficiency	Found that material choice and energy use in the wash cycle significantly affect total impact; stainless steel has high recyclability but energy-intensive production.	Directly relevant baseline study for dishwasher environmental analysis.
Biganzoli et al. (2016)	Material Flow Analysis	End-of-life treatment and recycling efficiency of dishwashers	Demonstrated that up to 85% of dishwasher materials (mainly metals) can be recovered through proper recycling processes.	Supports the argument for design-for-disassembly and material reuse in dishwashers.
Ardente & Mathieux (2014)	LCA and Ecodesign Assessment	Environmental improvement potential in dishwashers through design optimization	Suggested that integrating eco-design principles could reduce overall impacts by 10–20%.	Highlights the potential of sustainable design strategies for dishwashers.

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Bovea et al. (2020)	Life Cycle Assessment (LCA)	Environmental evaluation of household appliances using recycled materials	Demonstrated that replacing virgin plastics with recycled polymers reduces GHG emissions by 25–35%.	Provides quantitative support for using recycled polymers in dishwasher components.
Parente et al. (2022)	Comparative Material Study	Use of bio-based polyamides and PLA in household appliances	Found that bio-based materials reduce fossil dependence but have limitations in thermal resistance.	Highlights trade-offs between performance and sustainability.
Matsumoto et al. (2021)	Circular Economy Framework	Integration of circular design in home appliance manufacturing	Design-for-disassembly increases recyclability and component reuse by 40–60%.	Reinforces circular design approaches applicable to dishwashers.
Cucuzzella & Salvia (2019)	Design for Sustainability Review	Sustainable design principles for durable consumer products	Identified that modularity and material reuse extend product life and reduce waste.	Provides a theoretical framework for sustainable dishwasher design.
Zanghelini et al. (2020)	Environmental Performance Assessment	Substitution of metals with recycled or hybrid materials in appliances	Substituting virgin metals with recycled alloys cuts embodied energy by 20–30%.	Relevant for replacing metallic dishwasher components sustainably.
Molina-Moreno et al. (2018)	Industrial Case Study	Eco-design implementation in appliance manufacturing	Reported 18% reduction in production waste after eco-design integration.	Demonstrates practical feasibility of sustainability strategies.