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Eco-efficiency Measures for Sustainability

Introduction

Throughout history, geo-resources have played a fundamental role in enabling technological progress and economic development by providing the raw materials required for infrastructure, products, and innovation. However, the increasing intensity of resource extraction and consumption has led to significant environmental degradation, including pollution, ecosystem disruption and growing resource scarcity. In the context of the accelerating climate crisis, there is an urgent and rising need to rethink how products are designed, produced, used and disposed of. Technological solutions, particularly those involving electronic components, contribute not only to societal benefits but also to lifecycle emissions and material demands, making sustainable engineering more important than ever.

Sustainable engineering aims to address these challenges by balancing environmental protection with economic viability and social well-being. It is therefore grounded in the three pillars of sustainability: environmental responsibility, economic performance, and social equity. This idea is aligned with the 17 Sustainable Development Goals (SDGs) established by the United Nations **[1]**, which provide a global framework for coordinated climate action. Addressing climate change requires not only large-scale systemic transformations but also many small improvements, innovative technologies, and incremental design decisions that collectively reduce environmental impacts and support more resilient consumption patterns.

Within this broader context, technological innovations such as smart consumer products like TRAQUA can play a meaningful role. Consequently, this chapter examines sustainability from a general and holistic perspective in relation to TRAQUA. First, the relevant SDGs connected to the product are introduced. Subsequently, sustainability is analysed in detail from the environmental, economic, and social perspectives. Finally, a Life Cycle Assessment (LCA) of TRAQUA is conducted to systematically evaluate its environmental impacts throughout the entire life cycle **[2]**, thereby identifying potential hotspots and opportunities for improvement.

UN Sustainable Development Goals

Table 1 lists the UN Sustainable Development Goals associated with the smart water bottle.

Table 1: SDGs

SDG	**Justification**
	Goal 3: This goal focuses on ensuring healthy lives and promoting well-being for all at all ages. A smart bottle can support this by encouraging regular hydration, ensuring the consumption of clean drinking water by purifying the water and the bottle and filtering it and helping users develop healthier daily routines through tracking and reminders.
	Goal 6: This goal aims to ensure access to and the sustainable management of water and sanitation for all people. By building trust in tap water through hygiene support and filtration features, a smart bottle can promote safer daily water consumption and reduce reliance on commercially available bottled water.

SDG	Justification
	Goal 12: This goal promotes sustainable resource use and waste reduction across product lifecycles. A durable, repairable, and recyclable smart bottle can help reduce single-use plastic consumption and encourage more responsible hydration habits.
	Goal 13: This goal focuses on combating climate change and reducing greenhouse gas emissions. By reducing the demand for transported bottled water and promoting local production and long product lifecycles, a smart bottle can help reduce the overall carbon footprint associated with drinking water consumption. However, this approach only works when compared to single-use or returnable plastic bottles, and not when compared to standard reusable bottles.

Environmental

The environmental impact of the smart bottle concept can be understood on two main levels. On the one hand there is the influence of the user's behavior and on the other hand the ecological footprint of the product itself.

On the behavioral level, the product aims to encourage people to change their purchase behavior, moving away from single-use or PET bottles, and buy TRAQUA. There are several reasons consumers provide for preferring bottled water over tap water. Some see it as the only option for clean water, for some it is a symbol of status and the modern lifestyle, for others it is simply more convenient, handier, or tastier than tap water **[3]**. TRAQUA faces these reasons to increase users' confidence in drinking tap water by providing hygiene support and transparency about bottle cleanliness. In particular, people who do not use standard reusable water bottles due to concerns about the quality of tap water become carefree through the smart bottle and change their consumption habits. This can reduce the perceived need to purchase bottled water in single-use or even additional reusable containers.

Over time, this behavioral change can lead to significant reductions in plastic waste. Per-capita consumption of bottled water has been increasing continuously and represents the fastest-growing segment within the packaged beverage industry, with projected annual growth rates of around 10 % up to 2026 **[4]**. The majority of bottled water is distributed in PET plastic containers, which contribute to environmental impacts throughout the entire product lifecycle, including raw material extraction, production, transportation, and waste management. Plastic bottles require a lot of energy to manufacture, require a complex transportation infrastructure, and are difficult to recycle and clean. They are partly responsible for plastic pollution in the oceans. Carbon dioxide equivalents (CO_2 eq) are used to measure a product's environmental impact. This allows for a comparison of the impact of various products on the greenhouse effect; to this end, all greenhouse gases emitted during the life cycle are quantified based on their environmental impact. The greenhouse gas emissions over the life cycle of a 500 ml PET water bottle amount to 3.87 kg CO_2 eq **[5]**.

If, for example, a person typically consumes one single-use plastic bottle per day, switching entirely to tap water could prevent the use of more than 700 plastic bottles over two years. This demonstrates how improved trust in local drinking water and bottle hygiene can contribute to more sustainable consumption habits.

On the product level of TRAQUA, sustainability is addressed through material and design choices.

A reflective material is required for UV cleaning. Theoretically, aluminum, stainless steel, and

Polytetrafluorethylen would be suitable options. Teflon was ruled out due to health risks and carcinogenic substances. Since steel is heavier and more expensive than aluminum, and aluminum reflects light better due to its surface properties, aluminum was chosen. For reasons of weight and durability, plastic is used for the outer bottle The use of recyclable aluminium and selected plastics supports circular resource use and reduces environmental impact at the end of the product's lifecycle. The system is designed with durability in mind, including long-lasting technical components and a battery with sufficient lifespan. Modular construction allows critical parts such as filters or electronic components to be replaced individually, extending the overall product lifetime.

A common reason for replacing conventional reusable bottles is the buildup of dirt or microbial contamination over time. By integrating active hygiene support such as UV-based cleaning, the product can reduce this issue and encourage longer use. This contributes to waste prevention by lowering the frequency of product replacement.

Additional environmental benefits can be achieved through local manufacturing and local distribution strategies. Producing and marketing the product regionally can reduce transportation distances, associated emissions, and packaging requirements. Finally, designing the product for disassembly and recyclability supports responsible end-of-life management and resource recovery. Together, these behavioral and technical sustainability measures contribute to a solution that not only reduces plastic waste but also promotes long-term environmentally responsible usage of TRAQUA.

Economical

Economic sustainability in the TRAQUA concept focuses on creating a balance between economic growth, long-term user value, and ecological benefits. The product is designed to deliver financial advantages to both consumers and producers while supporting more sustainable consumption patterns.

One important factor is the long lifespan of the product. By using durable materials and integrating repairable and replaceable components, the bottle can remain functional for many years. This reduces the need for frequent replacements and lowers the total cost of ownership for users. Repairability also supports local service opportunities and reduces economic losses associated with early product disposal.

From a cost perspective, the product can be competitive when compared to regular bottled water consumption. For example, TRAQUA will be priced at around 100 € can replace the use of approximately 700 single-use plastic bottles over two years, depending on individual drinking habits. This represents not only an environmental benefit but also potential financial savings for consumers over time.

Local production and local selling strategies can further strengthen economic sustainability. Selling through regional retailers as well as online platforms supports local economies, reduces transportation costs, and increases product accessibility. At the same time, it allows companies to build closer relationships with customers and respond more effectively to market needs.

Social

Smart hydration solutions can improve everyday life by removing the need to regularly buy and carry single-use plastic bottles, allowing consumers to gain greater flexibility and independence in their daily routines. By relying confidently on tap water, users can hydrate wherever they are without planning purchases in advance or transporting heavy bottles. This supports more convenient, mobile lifestyles while reducing everyday stress related to access to safe drinking water.

Integrated hygiene support also reduces the effort required to manually clean reusable bottles, leading to time savings and more consistent usage. Filtration features can help maintain a pleasant taste. At the same time, social sustainability requires acknowledging potential challenges. Safety concerns related to technologies such as UV-C disinfection and integrated electronics must be carefully addressed through responsible engineering design, as discussed in the engineering ethics chapter. In addition, the price of a smart bottle is likely to exceed that of a conventional reusable bottle, which means that not all users will be able to afford it despite efforts to keep the product relatively accessible.

Through tracking functions, users can better monitor their drinking behavior and stay aware of their hydration levels. This is particularly beneficial for individuals who struggle to drink enough due to busy schedules or health-related challenges, as reminders and feedback can support healthier routines and strengthen awareness of their body’s needs. This can improve overall well-being and support more conscious self-care in everyday life. Inclusivity is also an important social aspect. Features such as voice control or simple feedback signals can make the product more accessible for visually impaired users or people with different levels of technological familiarity.

Compared to conventional tap water use without additional treatment, hygiene and filtration functions can increase perceived safety and comfort. At the same time, avoiding bottled water reduces potential exposure to microplastics and contributes to a higher overall quality of life through more sustainable and health-conscious consumption habits.

Life Cycle Analysis

Life Cycle Assessment (LCA) is a standardized, scientific methodology used to evaluate the environmental impacts of a product throughout its entire lifespan. Often referred to as a “cradle-to-grave” analysis, it quantifies resource consumption and emissions at every stage.One crucial task is to assess how each stage of the life cycle contributes to the overall environmental impact. This analysis is typically aimed at prioritizing enhancements in products or processes and comparing various products for internal purposes. Life Cycle Analysis (LCA) is a method for evaluating the environmental impact of a service or product throughout its life cycle, from design to end-of-life management. LCA or life cycle assessment is an essential tool to support sustainable development decision-making, as well as to assess the potential environmental impacts of a product, material, process or activity **[6]**.

The following graphic illustrates the circular economy approach and the steps in an LCA in Figure 1.

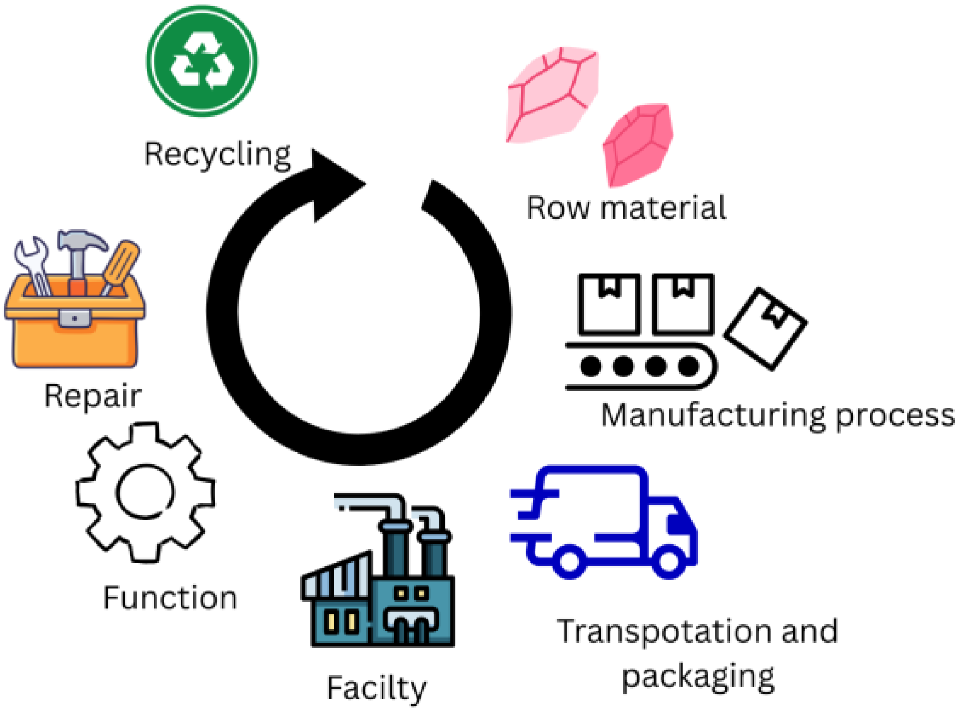

Figure 1: Life cycle analysis

Raw Material

Metal Components (Aluminium)

- Extraction of aluminium creates initial environmental impact through mining (using recycled aluminium)
- Aluminium is highly durable and recyclable, which reduces long-term resource consumption

Plastic Components (Container)

- They contribute to microplastic pollution and are more difficult to recycle (using recycled plastic)

Other components (battery, sensors, filter)

- Use of long-lasting materials lowers the need for frequent product replacement
- resource-intensive, involving rare earth elements and toxic chemicals

Manufacturing Process

- Aluminium: extremely high energy consumption during manufacturing, high melting point required, toxic fumes
- Plastic: less energy during production, high melting point required, toxic fumes
- Components: energy-intensive

Tansportation and Packaging

- Short transport routes from the raw product to the end of the bottle’s life cycle

- Keep the product as lightweight as possible to minimize transport costs and effort
- Transport by road and sea, not by air
- Focus on direct sales through local retailers and rely only minimally on online marketing
- Sustainable, reusable, and lightweight packaging materials and packaging designs that meet industry standards

Facilty

- Simple, step-by-step, user-friendly instructions for setting up the bottle

Function and use phase

- Encourages users to switch from bottled water to tap water, reducing plastic waste and transport emissions
- UV hygiene support increases confidence in reuse and extends product lifetime
- Hydration tracking can lead to behavioral change toward healthier and more sustainable consumption
- The filter must be replaced regularly
- Requires electricity for charging leads to a small ongoing environmental impact

Repair

- Replaceable filters and modular electronics allow maintenance without discarding the entire product
- Battery replacement can extend lifespan significantly
- Reduced cleaning effort due to hygiene functions encourages long-term consistent usage

Recycling

- Aluminium structure can be fully recycled, lowering lifecycle emissions
- Plastic can be recycled
- Electronics and battery must be separately collected and processed
- Battery recycling, discharging, thermal/chemical processing, separation into raw materials, reuse, circular economy

Table 2 presents the CO_2-equivalent emissions of the product across the different life cycle stages. The values should be understood as approximate screening results, as detailed primary data for all components were not available. Therefore, the electronic components were aggregated based on their total mass. For these components, as well as for the battery, datasets from the openLCA Nexus **[7]** were used. In general, average datasets for electronic components and material production from publicly available LCA databases were scaled according to component mass, which represents a common approach in early-stage life cycle assessments.

For the activated carbon filter, data from the EU Environmental Footprint Database provided by the European Commission Joint Research Centre were applied **[8]**. The values for the aluminium foil and the plastic bottle were taken from the German ÖKOBAUDAT database **[9]**. Furthermore, for the calculation of module C2 (transport), a transport distance of 1000 km by truck was assumed.

Table 2: CO_2-equivalent

Component / Material	**A1-A3 Production [kg CO_2-eq.]**	**C2 Transport [kg CO_2-eq.]**	**C3 Waste management [kg CO_2-eq.]**	**D Recycling potential [kg CO_2-eq.]**
Electronics assembly (157 g total)	4.71	0.02	0.20	-0.80
Battery	1.04	0.01	0.05	-0.30
Activated carbon	0.06	0.002	0.02	-0.03
Plastic bottle	0.60	0.01	0.10	-0.25
Aluminium foil	3.189	0.001	0	-2.103
Total	9.599	0.083	0.37	-3.485

A screening life cycle assessment based on publicly available datasets indicates that the TRAQUA product has a cradle-to-grave carbon footprint of approximately 6–10 kg CO_2-eq, with aluminium components and electronic assemblies representing the dominant environmental hotspots. Compared to a single-use plastic bottle with 3.87 kg CO_2-eq, this value of approximately 6 kg CO_2-eq. may seem very low. One reason for this could be the only broad assessment of the values for electronic components. For these, there are hardly any clear data sources; instead, one must rely on general comparative values. Additionally, the transport routes differ, and it is difficult to predict exact data for transport. However, the 1000 km estimate is considered too low, particularly for electronics. One reason for the comparatively high value of the single-use bottle is that, due to filling and the higher weight, its transport has a greater impact on the CO_2-equivalence than that of empty bottles. It should be emphasized that this LCA is more of an estimate than a precise calculation.

When the actual process flows in TRAQUA are known and realized, a more systematic LCA could be developed.

Following the breakdown of CO_2 equivalents, we now turn our attention to energy. Here, too, energy consumption is broken down by LCA phase, with the sources corresponding to those of the CO_2 equivalents. No distinction is made between renewable and non-renewable energy, as this is not done in all of the databases used. Table 3 shows the energy consumption.

Table 3: Energy consumption

Component / Material	**A1-A3 Production [MJ]**	**C2 Transport [MJ]**	**C3 Waste management [MJ]**	**D Recycling potential [MJ]**
Electronics	71	0.20	2.5	-8
Battery	12	0.10	0.8	-3
Activated carbon	2.5	0.05	0.3	-0.5
Plastic bottle	24	0.20	1.5	-5
Aluminium foil	38.73	0.015	0	-24.44
Total	148.313	0.565	5.1	-17.9

Summary

Based on this sustainability analysis, the team chose durable and recyclable aluminium and plastices as the main structural materials, modular electronic components, replaceable filters, and a long-life rechargeable battery for the following reasons: to reduce resource consumption over time, enable repairability and material recovery, and support long-term behavioral change toward drinking tap water instead of purchasing bottled water. In addition, strategies such as local production and distribution were considered to minimize transportation-related emissions.

Consequently, the team decided to design a solution with a long product lifespan, easy component replacement and integrated hygiene. This can improve user-friendliness, support fluid intake tracking to promote sustainable consumption habits, and, thanks to the easy-to-disassemble design, improve recycling outcomes at the end of the product's life cycle. These features aim to balance environmental impact during production with significant sustainability benefits during the use phase.

After examining TRAQUA from the perspective of sustainability, we now turn to the ethical and deontological perspectives. Both approaches are primarily applied during the planning phase of TRAQUA to inform decisions with arguments from both fields, but they also run horizontally throughout the entire development process so that

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[1] United Nations, 2026. *THE 17 GOALS.* [Accessed in April 2026].
[2], **[6]** Anders Bjørn, Mikołaj Owsianiak, Christine Molin, Alexis Laurent, 2017. *Life cycle assessment.* Berlin, Germany: Springer, ISBN 978-3-319-56475-3.
[3], **[4]**, **[5]** Yael Parag, Efrat Elimelech, Tamar Ophe, 2023. *Bottled Water: An Evidence-Based Overview of Economic Viability, Environmental Impact, and Social Equity in Sustainability.* [Accessed in March 2026]: MDPI.
[7] openLCA Nexus, 2026. *openLCA Nexus.* [Accessed in March 2026].
[8] EU Environmental Footprint Database, 2026. *EU Environmental Footprint Database.* [Accessed in March 2026].
[9] ÖKOBAUDAT, 2026. *ÖKOBAUDAT.* [Accessed in March 2026].