

Environmental Impact Analysis of Social Media Usage via Eco-Impact Tracker^{*}

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Abstract

The accelerating digitalization of society contributes an increasingly significant share of global carbon emissions, driven by energy-intensive data centers, network infrastructures, and the pervasive use of mobile devices. Yet individuals still lack accessible and trustworthy feedback on the environmental impact of everyday digital activities, including social media use, video streaming, and online collaboration. This report presents the Eco-Impact Tracker, a mobile application developed during Climathon Lappeenranta 2024, designed to increase user awareness of environmental impact as a foundational step toward more sustainable digital practices. The application monitors users' screen time and estimates their carbon footprint and battery consumption across social media platforms. Built with Flutter and informed by Greenspector's 2021 carbon emissions model, it delivers real-time eco-feedback through an intuitive interface. To evaluate its effectiveness, a controlled survey experiment was conducted with 20 participants, divided into a control group (using standard monitoring tools) and an experimental group (using Eco-Impact Tracker). Results showed a statistically significant improvement in awareness of the environmental impact of digital behavior among experimental participants compared to controls (Mann-Whitney $U = 18.0$, $p = 0.007$). These findings indicate that targeted eco-feedback in the digital domain can positively influence user awareness and attitudes toward sustainability. Eco-Impact Tracker thus functions not only as a tool for individual behavior change but also as a scalable model for bridging the gap between digital convenience and ecological responsibility within the broader landscape of behavior change support systems. Planned future releases will incorporate gamification, goal setting, reminders, qualitative data from interviews or focus group and richer data sources such as regional CO₂ intensity factors to enhance motivation and improve accuracy.

Keywords

Digital carbon footprint, social media impact, Environmental sustainability, User engagement, sustainable software engineering, Eco-feedback, Flutter, Persuasive technology.

1. Introduction

Digital technologies are deeply embedded in everyday life, with social networking platforms and mobile phones shaping communication, entertainment, and productivity. However, this convenience carries a largely hidden environmental cost: the electricity consumed by devices, networks, and data centers contributes substantially to global greenhouse gas (GHG) emissions. Current estimates place the ICT sector at approximately 1.8% to 4% of worldwide CO₂ emissions [5] [8], a footprint comparable to that of the aviation industry. Broader lifecycle assessments—including manufacturing and end-of-life processes—suggest that this figure may rise even higher, reaching 2.1% to 3.9% of global emissions [9].

Within this sector, social media use is one of the most energy-intensive digital activities. Continuous video streaming, algorithmic content delivery, and frequent media uploads require significant data processing and transmission. As a result, an individual's social media habits can

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carry unexpectedly high ecological costs. Studies estimate that typical social media activity can generate up to 60 kg of CO₂ annually [1], while broader digital content consumption may reach 229 kg of CO₂ per person per year, representing nearly 40% of the per-capita carbon budget aligned with the 1.5°C climate target [6][3]. Even everyday actions such as emailing contribute substantially to emissions, with global email usage estimated to produce 1.2 trillion grams of CO₂ per day [10].

Figure 1 illustrates how ICT-related emissions are distributed across manufacturing, network infrastructure, end-user devices, and digital content.

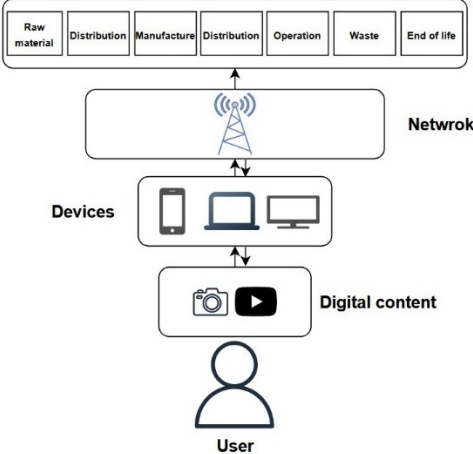


Figure 1: Lifecycle And Emission Flows of ICT Systems. Recreated from [6]

ICT-related emissions are not evenly distributed across the sector. As shown in Figure 2, User devices account for the largest share, approximately 57% of total emissions—followed by networks (24%) and data centers (18%) [7]. These patterns highlight the critical role of user behavior and device usage in shaping the environmental footprint of digital consumption.

Despite this impact, most users remain unaware of the carbon footprint associated with their digital behavior. Existing tools—such as Google’s Digital Wellbeing or built-in battery usage monitors—provide information on screen time and energy consumption but do not translate these metrics into environmental terms. This gap limits users’ ability to understand the broader sustainability implications of their digital practices.

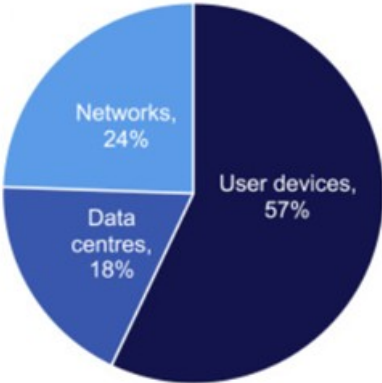


Figure 2: Estimated ICT-Related Carbon Emissions by Component [7]

The Eco-Impact Tracker app was developed to address this information gap by enabling users to measure the carbon footprint of their social media usage alongside battery consumption. By explicitly linking digital activity with its environmental consequences, the app aims to raise sustainability awareness and support awareness-building and reflection regarding digital behavior.

2. Background & related work

2.1. Persuasive system design

Persuasive technology refers to interactive systems designed to influence and change user behavior. In their work, [18] proposed a set of persuasive system design principles, grouped into four categories: primary task support, dialogue support, system credibility, and social support. These principles serve as guidelines for developing applications intended to encourage behavior change [18]. Within primary task support, key principles include reduction, which simplifies complex behaviors into manageable tasks; tailoring and personalization, which provide users with information relevant to their specific context; and self-monitoring, which enables users to track their own behavior over time. The dialogue support category includes principles such as praise for positive behavior, rewards that acknowledge user achievements, reminders that prompt users toward their target behavior, and suggestions that offer context-appropriate guidance. System credibility refers to the principle that a system should provide trustworthy and knowledgeable outputs grounded in real-world data, ensuring that users perceive the information as accurate and reliable. Finally, social support encompasses principles like social learning, which allows users to observe the behaviors and outcomes of others; social comparison, which enables users to compare their performance with peers; competition, which introduces opportunities to compete; and recognition, which highlights and reinforces users who successfully perform the desired behavior [18].

2.2. Eco-feedback technology

Eco-feedback can be understood as an extension of persuasive technology, as it uses interactive systems to influence user behavior toward more sustainable choices. Eco-feedback technology is defined as technology that provides individuals or groups with feedback about their behavior in order to reduce environmental impact. It is grounded in the assumption that people often lack awareness of the environmental consequences of their everyday actions, and that technology can help bridge this gap by automatically tracking these activities and presenting meaningful feedback [2].

Providing information about behavior is one of the most important components of environmental behavior change. However, simply presenting information is not sufficient. Feedback must be understandable, attention-grabbing, and delivered at an appropriate moment to be effective. While behavior change is the central goal of eco-feedback systems, achieving measurable change requires extended observation and long-term engagement, making it a challenging area to evaluate within short study periods [2]. This is also supported by other research, which shows that behavior change is a gradual learning process that evolves over time [19] and awareness is one of the first steps towards behavior change [22], [23].

2.3. Related work

Limited research has been conducted on mobile applications that specifically track the carbon footprint of social media usage. However, several studies have explored eco-feedback systems and broader digital sustainability tools.

Previous research [11], [14] identified several applications available on the Google Play Store to track digital carbon footprints. One example is Pawprint, launched by Christian Arno, which helps users track and reduce their carbon footprint by making more sustainable lifestyle choices [12]. Another related platform, Earth Hero: Climate Change [13], was developed to support carbon-reduction efforts and encourage community engagement. However, these applications do not provide personalized recommendations tailored to individual user behaviors.

Sampath, K. and Srilatha, Y[14] introduced a mobile application, EcoEdge, designed to track an individual's carbon footprint based on daily activities such as travel, food choices, and shopping. The app provides visual feedback to encourage users to adopt more sustainable habits.

Researchers have been applying different techniques to motivate individuals via digital technology to change their behavior such as point-based rewards were utilised by [24] with offering badges to top-performing users, while others focused on feedback an effective way to persuade people towards positive behavior change [25]. Another platform, EcoTrack, was introduced in recent research [11] as a user-friendly platform designed to help individuals reduce their carbon footprint by making more sustainable choices. The app also integrates gamification and a reward system to incentivize and reinforce sustainable behaviors.

A further smartphone application, Monochrome was proposed by [15] based on the iTRACE-IT framework. The app tracks an individual's weekly emissions generated through the use of external applications on their smartphone. By providing this information, the application aims to raise awareness and motivate users to reduce their digital carbon footprint.

Previous research has introduced applications such as EcoEdge and EcoTrack to help users explore their carbon footprint. However, a major limitation of both systems is their reliance on manual data entry, which places additional burden on users and increases the likelihood of inaccurate or incomplete logs. Moreover, none of these tools specifically targeted the carbon impact of social media usage, despite its significant contribution to digital emissions. Although applications like Monochrome have attempted to track emissions from external apps, they have not been evaluated in a controlled experimental setting, leaving their effectiveness in influencing user behavior largely untested.

3. Methodology

This chapter presents the design and development of the Eco-Impact Tracker, outlining the system architecture, development environment, workflow, and key interface components. It also describes how sustainability principles were incorporated into the app's overall design. Following this, the chapter presents the evaluation of the application, detailing the methods used to assess its impact.

3.1. System overview

The Eco-Impact Tracker was developed as an Android application using Dart and the Flutter framework, implemented in Visual Studio Code. Flutter was selected due to its cross-platform capabilities and efficient UI rendering, while Dart provided the reactive programming structure required for real-time data visualization. The system design of the Eco-Impact Tracker focuses on accurately quantifying and clearly displaying the carbon footprint associated with users' digital energy consumption.

3.2. Persuasive and sustainability-driven design principles

Reflecting on the persuasive system design principles outlined by [18], the Eco-Impact Tracker was developed as an interactive system intended to influence user behavior by increasing awareness of the environmental impact of social media use. The design incorporates key PSD categories—primary task support, dialogue support, and system credibility—through an easy-to-use interface that translates advanced data into simple, comprehensible insights.

The main operation of the app is organized into a clean, minimalist interface that guides the user through several stages of analysis, from real-time tracking to long-term history of their digital carbon footprint. This emphasis on simplicity and clarity aligns with reduction, a primary task support principle that simplifies complex environmental data into manageable, meaningful information. The home dashboard provides an immediate overview of instantaneous CO₂ emissions and battery usage for a selected social media application, helping users understand how their

current actions directly contribute to their carbon footprint. This home screen serves as the main entry point to the app's feature and analysis areas (Figure 3).

A maintained list of available social media platforms allows users to easily select and view information for specific apps, reflecting the PSD principles of tailoring and personalization, which ensure that feedback is relevant to each user's context. The side navigation menu remains minimal yet includes essential sections—Usage Stats, Total Impact, and Analysis—supporting self-monitoring, another primary task support principle that enables users to track their behavior over time. This structure also facilitates comparison across platforms, allowing users to identify which apps contribute most to their carbon footprint.

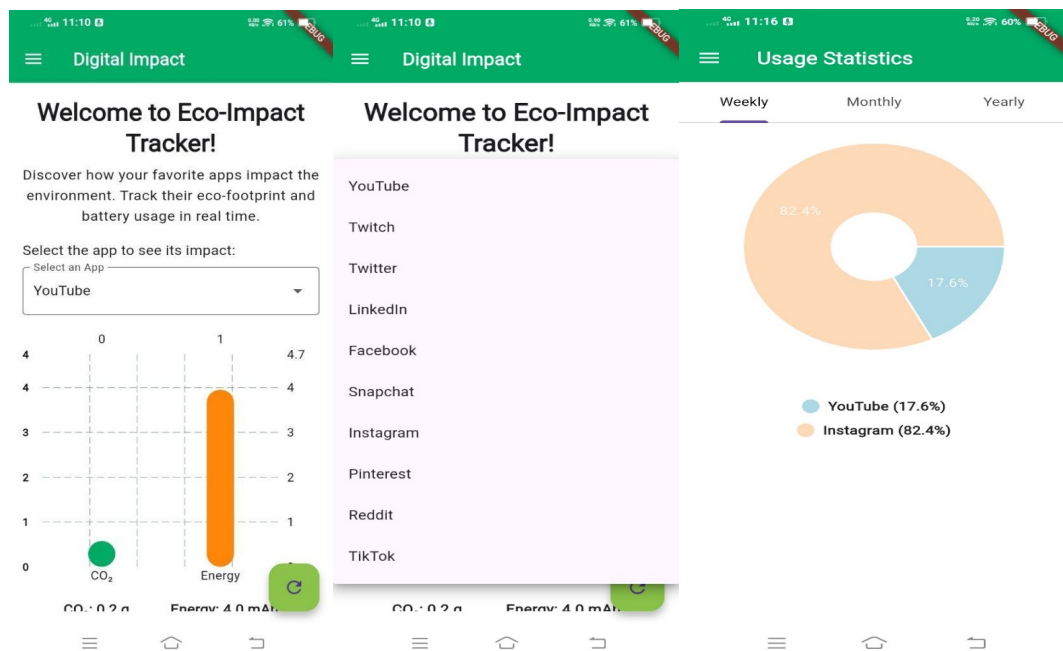


Figure 3: Home Screen (Left), List of Social Media Apps (Middle) and Usage Statics Screen (Right)

Information is displayed graphically through pie charts and bar charts, illustrating emissions and battery utilization across daily, weekly, and monthly intervals (see Figure 3). These visualizations function as feedback mechanisms, a core element of dialogue support, making invisible emissions visible and prompting users to reflect on their long-term digital habits. By presenting real-time and historical eco-feedback, the app provides suggestions—recognized PSD dialogue support strategies that help guide users toward more sustainable digital practices. The Eco-Impact Tracker was created with the explicit purpose of embedding sustainability values into its functionality. It is more than a monitoring tool; it is designed as a persuasive technology that supports awareness and reflection by making the environmental footprint visible. This is achieved through three integrated design principles:

Translating Digital Consumption into Environmental Cost - The central idea of the app is to convert abstract units of digital consumption—such as screen time and battery use—into concrete environmental metrics, namely CO₂ emissions. This aligns with the persuasive principles of reduction and tailoring, simplifying complex environmental data and presenting it in a personalized, meaningful way [18].

Giving Feedback Loops - The application is built around continuous eco-feedback, a well-established persuasive strategy. Providing users with real-time and historical feedback on their digital carbon footprint supports self-monitoring, one of the primary task principles, while also functioning as reminders and suggestions under dialogue support [18].

Enabling Awareness Building - The design of the Eco-Impact Tracker supports UN Sustainable Development Goal (SDG) 12, Responsible Consumption and Production, directly. By encouraging

awareness of the carbon price of online consumption, the app helps raise awareness among its users regarding the environmental cost of a modern lifestyle in today's digital age. Awareness building is a basic step towards creating a culture of sustainable digital living.

3.3. System architecture

The system architecture consists of four individual layers, each of which performs a specific activity, such that they create a seamless flow of data collection to user response. Figure 4 shows the system architecture of Eco-Impact Tracker.

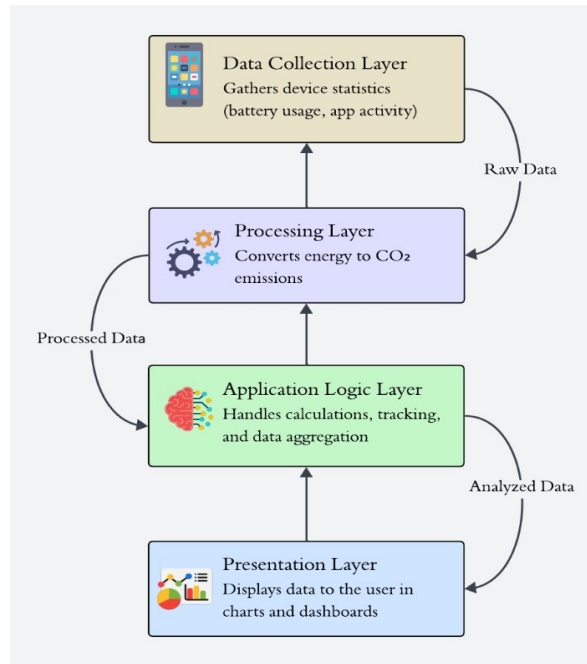


Figure 4: System Architecture of Eco Impact Tracker

3.3.1. Data collection layer

This is the base layer of the system. It gathers raw data straight from the user's device. Taking advantage of the APIs system on Android, the app retrieves detailed statistics on device usage like battery use, app use, and screen time. This data serves as the input to the whole system and provides the necessary metrics to calculate energy consumption and ultimately carbon emissions.

3.3.2. Processing layer

The processing layer is the analytical brain of the system. It is essentially used to convert raw energy usage data into approximated CO₂ emissions. This is achieved by applying published emission factors, which are normalized values that correlate a unit of energy (e.g., kilowatt-hour, kWh) with a corresponding amount of CO₂ emissions (e.g., grams of CO₂ per kWh). This layer integrates the processed data from all the individual apps into a separate environmental profile for each.

3.3.3. Application logic layer

This layer is the "brain" of the application, responsible for internal processes and user-specific logic. It is charged with a variety of functions, including app selection and calculation logic, determining which apps to track and how to apply the emission factors. It also handles the implementation of usage tracking, so that the system has the ability to track and store day-to-day,

week-to-week, and month-to-month usage patterns. In addition, it manages data aggregation, collecting all the processed data in a form that can be easily reported to the user.

3.3.4. Presentation layer (UI/UX)

The bottom rung of the architecture deals with the user interface. Its role is to display results clearly, intuitively, and interactively. It achieves this by employing a range of visualization methods, including bar charts and pie charts graphically display the carbon footprint of different apps, summary dashboards that provide an at-a-glance overview of impact overall and a navigation menu (e.g., Home, Usage Stats, Total Impact, Analysis) that allows the user to change views and insights easily and get actionable feedback in order to encourage sustainable digital behavior.

3.4. Evaluation method

3.4.1. Study design

The primary objective of this evaluation was to determine whether the app increased user awareness of the environmental impact of social media usage compared to conventional monitoring tools such as Android Digital Wellbeing and Battery Monitor. A controlled survey-based experiment was conducted with 20 participants, equally divided into a control group and an experimental group:

1. Control Group – employed existing monitoring tools (Android Digital Wellbeing and Battery Monitor).
2. Experimental Group – employed the Eco-Impact Tracker app

Participants included students, software engineers, teachers, and other professionals who frequently engage with social media. They were invited via email and text message and took part in the study voluntarily. Participants used their assigned tool for one week and completed a structured Google Form survey. Quantitative (Likert-scale) responses were collected and analyzed.

3.4.2. Data collection

All participants were instructed to use the tool assigned to them for seven days and then complete an online, guided individual survey. The survey included Likert-scale items measuring usability, awareness, reflection, and motivation, along with space for open comments. It consisted of the following components:

Demographic measure: Daily average social media usage (<1 hour, 1–3 hours, 4–6 hours).

Six Likert-scale items (1 = strongly disagree, 5 = strongly agree):

- 1) Ease of use
- 2) Insights provided
- 3) Awareness of environmental impact
- 4) Reflection on digital carbon footprint
- 5) Motivation to reduce usage
- 6) Belief in sustainable digital practices

A total of 20 valid responses were collected between 1–13 August 2025. Each participant completed the survey individually after using their assigned tool for one week. Once responses were collected, they were labelled according to group allocation (Control or Experimental). The first ten responses corresponded to participants in the control group, while the remaining ten corresponded to participants in the experimental group. This labelling allowed the dataset to be structured for statistical comparison between groups. Following the collection of responses, they were coded according to group assignment (Experimental or Control) to allow statistical comparison. The grouping ensured that variation in sustainability knowledge resulted from the app effect directly.

3.4.3. Data analysis

Descriptive analysis [16] was first used to examine participants' daily social media usage, providing a basis for assessing comparability between the control and experimental groups. To determine whether the observed differences between the groups were statistically significant, a Mann–Whitney U test [17] was conducted on the survey responses. This test was appropriate because the data were collected using Likert-scale items (ordinal data) and the sample size was relatively small ($n = 20$). The hypotheses for the analysis were:

1. Null Hypothesis (H_0): There is no significant difference in sustainability awareness between the control and experimental groups.
2. Alternative Hypothesis (H_1): The Eco-Impact Tracker significantly increases sustainability awareness compared to existing tools.

4. Results

4.1. Descriptive analysis

The results showed an equal distribution of usage levels across both the control and experimental groups (see Figure 5). Specifically, 45% of participants reported using social media for 1–3 hours per day, and 40% reported more frequent use of 4–6 hours per day. A smaller proportion, 15%, reported minimal or less than one hour of use each day. As both groups shared the same distribution of baseline social media usage, this allowed for survey results to be compared on an even basis, with differences in awareness or attitudes being confidently attributed to the Eco-Impact Tracker rather than to underlying differences in usage patterns.

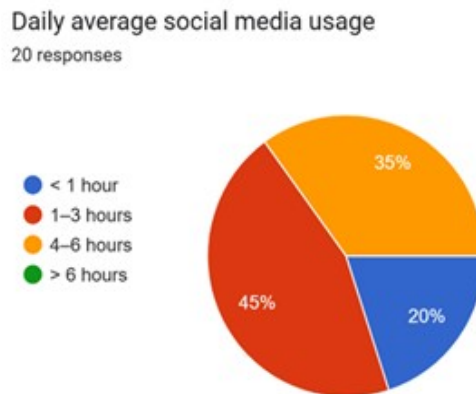


Figure 5: Daily Average Social Media Usage

Table 1 presents descriptive statistics for the survey items. Awareness scores were higher in the experimental group (mean = 4.0, median = 4.0) compared to the control group (mean = 3.1, median = 3.0), indicating that the Eco-Impact Tracker increased participants' awareness of the environmental impact of social media usage. Reflection scores were similar across groups, with a slight increase in the experimental group (mean = 3.4 vs. 3.2). Motivation scores were nearly identical (3.1 vs. 2.9), suggesting that short-term use did not influence motivation. Belief in sustainable digital practices was stronger in the experimental group (mean = 3.8, median = 4.0) than in the control group (mean = 3.2, median = 3.0).

Table 1

Descriptive Statistics of Awareness-related Items ($n = 20$)

Survey Item	Control Mean \pm SD	Control Median	Experimental Mean \pm SD	Experimental Median	p-value*
Ease of Use	4.2 \pm 0.63	4.0	4.1 \pm 0.57	4.0	0.820
Insights Provided	3.5 \pm 0.71	3.5	4.3 \pm 0.48	4.5	0.012
Awareness	3.1 \pm 0.88	3.0	4.0 \pm 0.47	4.0	0.007
Reflection	3.2 \pm 0.79	3.0	3.4 \pm 0.70	3.5	0.593
Motivation	3.1 \pm 1.10	3.0	2.9 \pm 0.74	3.0	0.780
Belief	3.2 \pm 0.63	3.0	3.8 \pm 0.63	4.0	0.060

4.2. Inferential analysis

The Mann–Whitney U test showed that the experimental group reported significantly higher awareness (median = 4.0) than the control group (median = 3.0), with $U = 18.0$ and $p = 0.007$. Therefore, the null hypothesis is rejected, confirming that the Eco-Impact Tracker increased awareness of the environmental impact of social media usage. For the remaining survey items, no statistically significant differences were found (Table 2). Reflection scores did not differ significantly ($U = 43.0$, $p = 0.593$), and motivation scores were also similar across groups ($U = 54.0$, $p = 0.780$). Belief in sustainable digital behavior was higher in the experimental group, but the result was borderline and not statistically significant at $p < 0.05$ ($U = 27.0$, $p = 0.060$).

Table 2

Mann–Whitney U Test Results (n=20)

Survey Item	Median (Control)	Median (Experimental)	U-value	p-value	Result
Awareness	3.0	4.0	18.0	0.007	Significant
Reflection	3.0	3.5	43.0	0.593	Not significant
Motivation	3.0	3.0	54.0	0.780	Not significant
Belief	3.0	4.0	27.0	0.060	(Borderline, not significant at $p < 0.05$)

4.3. Visual comparison between groups

Figure 6 shows the boxplot comparing awareness scores between groups. The experimental group's scores were centered around 4, while the control group's were centered around 3, with greater variation and a low outlier in the control group. This visual pattern aligns with the statistical results, indicating higher awareness among participants using the Eco-Impact Tracker. The bar

chart in Figure 6 illustrates average scores for awareness, reflection, motivation, and belief. The experimental group scored higher for awareness and belief, while reflection was slightly higher, and motivation remained similar across both groups. These patterns highlight the Eco-Impact Tracker’s impact on raising awareness and positive attitudes toward sustainability within a short-term study.

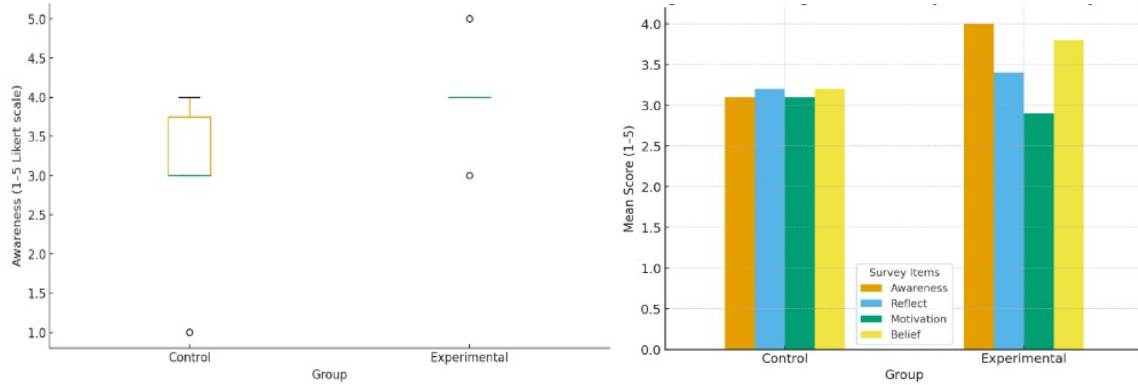


Figure 6: Awareness Score by Group (Left) and Average Sustainability-related Scores by Group (Right)

5. Discussion

The results demonstrated that the Eco-Impact Tracker significantly enhanced users’ awareness of the environmental effects of social media use. Awareness scores were notably higher in the experimental group compared to the control group, with the Mann–Whitney U test confirming statistical significance. This suggests that even short-term exposure to eco-feedback features—such as per-app CO₂ tracking and battery-usage insights—can positively influence users’ understanding of their digital carbon footprint. Unlike applications from previous research [14], [11], the Eco-Impact Tracker does not rely on manual data entry. Instead, it automatically collects raw usage data directly from the user’s device, reducing user burden and improving the accuracy and completeness of the information gathered. This automated approach may also contribute to the stronger awareness outcomes observed in the experimental group.

Although following the persuasive system design principles [18], reflection and motivation scores did not differ significantly between groups, this pattern aligns with earlier research [2], which indicates that behavior change typically requires longer exposure and repeated reinforcement through mechanisms such as gamification [18], nudges, or reward systems [18]. Over time, increased awareness can lead to meaningful changes in behavior as sustainable habits gradually take shape. [22], [23]. Participants in the experimental group also expressed stronger belief in the value of sustainability tools compared to the control group, with a p-value of 0.060—suggestive, though not statistically conclusive. This trend indicates that the Eco-Impact Tracker may foster trust and enthusiasm toward digital sustainability practices, but confirming this effect would require a larger sample or longer follow-up period.

These findings are consistent with previous studies [2], [19] showing that dynamic, personalized eco-feedback systems outperform static educational approaches in raising awareness and engagement. Visualizing environmental data encourages early engagement but does not immediately translate into behavioral change [2], [19]. This mirrors the present results: the Eco-Impact Tracker effectively increased awareness, yet motivation remained relatively unchanged within the one-week timeframe. Evidence from previous research further suggests that habit formation typically requires sustained exposure over several weeks or months [20], [21] often supported by gamification features or social comparison mechanisms. The strong awareness gains observed here indicate that the app can serve as an effective entry point for longer-term sustainability interventions. The findings also highlight the importance of embedding sustainability

into everyday digital practices. Social media platforms are substantial consumers of energy and carbon emissions, yet these impacts remain largely invisible to end-users [8]. By presenting real-time environmental data, the Eco-Impact Tracker addresses this critical awareness gap. Although behavioral motivation did not differ significantly between groups, awareness is a necessary precursor to behavior change. The app's ability to strengthen users' belief in sustainable digital practices suggests promising scalability as a tool for promoting sustainable consumption—particularly when paired with long-term engagement strategies.

6. Limitations

The study relied on a relatively small sample size ($n = 20$), which reduces statistical power and makes it more difficult to detect subtle differences between groups. In addition, the testing period lasted only one week—a duration typically insufficient for users to form new habits or meaningfully adjust their behavior. While the experimental group reported higher awareness, this timeframe does not allow for the observation of long-term habit formation or the decay of the 'novelty effect' associated with the application. Furthermore, the absence of richer qualitative feedback limited the depth of insight; open-ended responses could have revealed more regarding usability perceptions and emotional engagement with the tool. Regarding participant demographics, users were not significantly affected by the language factor when the Eco-feedback tracker was in English. However, cultural backgrounds may have a more pronounced effect, particularly as Finland's population of international students and immigrants has increased recently. This suggests a need for future research to investigate how diverse cultural backgrounds influence reactions to Eco-feedback [26].

7. Conclusion

This study introduced and evaluated the Eco-Impact Tracker, a mobile application designed to raise awareness of the environmental footprint of social media usage. By monitoring screen time, battery consumption, and estimating per-app CO₂ emissions, the app provides users with clear and actionable eco-feedback. In a one-week-controlled experiment with 20 participants, the Eco-Impact Tracker significantly increased users' awareness of the environmental impact of their digital behavior (median = 4.0 vs. 3.0; $U = 18.0$, $p = 0.007$). Participants also showed stronger belief in sustainable digital practices, although this difference approached but did not reach statistical significance. Reflection and motivation did not differ between groups, suggesting that while awareness can be raised quickly, meaningful behavior change likely requires longer engagement. Overall, the findings demonstrate that eco-feedback mechanisms—particularly per-app CO₂ tracking and usage summaries—are effective tools for addressing the visibility gap surrounding the digital carbon footprint. The Eco-Impact Tracker offers a scalable and user-friendly approach to increase sustainability awareness into everyday digital routines, going beyond existing monitoring tools by foregrounding the environmental cost of digital activity. This study contributes to the emerging field of digital sustainability by introducing a lightweight, data-driven carbon-awareness tool, showing that awareness can be raised even within a short intervention, and outlining a foundation for future behavior-change strategies. Building on these findings, the next stage of the research will extend these experiments to span a number of months to observe the extent to which heightened environmental awareness actually leads to behavior change, like lowering screen time or engaging more energy-conscious digital activities. Future work should incorporate gamification, goal setting, reminders [27], qualitative data from interviews or focus group and richer data sources such as regional CO₂ intensity factors to enhance motivation and improve accuracy.

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Declaration on Generative AI

During the preparation of this work, the authors used Grammarly to improve the language and readability of the manuscript. Additionally, Microsoft Copilot were utilized as technical aids to assist in debugging the Python code used for data analysis. All code outputs were independently verified and tested by the authors to ensure accuracy and reproducibility. The authors take full responsibility for the integrity of the final manuscript and the underlying computational results.

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