Gamification for Enhanced Recycling Engagement in Circular Economies

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Abstract: Global waste generation continues to rise, with current estimates ranging between 7 and 10 billion tons annually (Alvarez-Risco et al., 2022). Although Germany operates one of the most advanced recycling systems worldwide, its complexity - characterized by strict multi-bin separation rules, regional sorting variations, and the growing use of mixed-material packaging - presents significant challenges for residents. Additionally, public motivation to sort waste correctly is declining. The Transformers project addresses these challenges by developing a gamified, web-based application designed to promote correct recycling behaviour through interactive, educational, and motivational elements. This digital tool is part of a broader initiative to boost material recycling through digital innovation and encouraging active public involvement. By combining proven learning strategies with immersive gamification elements, the application significantly improves knowledge retention and fosters deeper user engagement in recycling activities. The gamification strategy and learning modules were developed based on interviews with experts from the recycling industry. A mixed methods approach also encompassed a design sprint with citizens and representatives of public authorities. Key features of the application include sorting simulations, knowledge quizzes, challenge-based activities, a personalised dashboard, weekly leaderboards, and progress summaries. Educational content is delivered through structured modules, gamified tasks, interactive games, and an integrated Recycling News Hub. A point-based rewards system further incentivises participation, enabling users to redeem their points for sustainable rewards. Future developments will integrate artificial intelligence to offer personalised recommendations, adaptive learning pathways, real-time chatbot assistance, and natural language processing-based summaries of recycling news.

Keywords: Digital engagement, Game-Based learning, AI-Enhanced learning, Public participation in recycling, Sustainability, Behavioural change

1. Triggering Action in an Era of Growing Waste

Recycling represents a central pillar of sustainable urban development and circular economies. As global consumption rises, recycling offers substantial opportunities for reducing raw material use and lowering carbon emissions. Despite Germany's advanced infrastructure with multi-bin systems and regulations, participation rates remain low, and recycling infrastructures are underdeveloped in many regions (Konstantinidou *et al.*, 2024). Research studies show that barriers to effective recycling systems are primarily behavioural, including knowledge gaps, operational complexity, and motivational challenges (Timlett and Williams, 2008a). Germany provides an advanced recycling infrastructure with a multi-bin separation system, regional logistics, and adequate regulations. However, inconsistencies in sorting rules and the growing prevalence of mixed-material packaging cause incorrect waste separation (Dahlén and Lagerkvist, 2010) which leads to an increased contamination of recyclable materials, lower recycling rates, and declining participation rates (Konstantinidou et al., 2024). Especially the dwindling acceptance is crucial, as effective recycling systems rely on more than only high-quality infrastructure; they require sustained public engagement. As Timlett and Williams argue, participation declines without ongoing guidance, personalised feedback, or motivational incentives (Timlett and Williams, 2008a). Sustained engagement demands continuous behavioural reinforcement. Behavioural research identifies psychological and social factors hindering recycling participation, e.g. invisible impact, lack of social recognition, inconsistent sorting instructions, and insufficient feedback mechanisms (Timlett and Williams, 2008a; Konstantinidou *et al.*, 2024). These barriers are especially relevant among diverse urban populations, including international residents unfamiliar with local rules. Regarding that, digital participation solutions offer a variety of new ideas and approaches, particularly those using advanced motivational mechanisms like gamification. Game elements such as challenges transform mundane tasks into interactive and rewarding experiences. In terms of personal feedback and adaptive content, AI solutions offer a variety of new possibilities. As Vegesna highlights, future digital sustainability solutions will integrate AI-powered features for real-time personalised support, predictive feedback, and context-aware engagement (Vegesna, 2023). Building on these foundations, this research investigates how a gamified platform can foster correct recycling behaviour through interactive learning modules, challenge-based participation, real-time feedback, and social incentives. In the

Transformers project funded by the Ministry of Culture and Science of North Rhine-Westphalia in Germany we developed the Transformers-App through a participatory design approach involving municipal experts, recycling professionals, and citizens. The app aims to create sustainability knowledge in a broadly diverse population and transfer it into measurable action. The approach builds on the principles of circular economies. By aligning gamified learning with adaptive engagement strategies, this study contributes to the field of sustainability education and digital behaviour change bridging the gap between recycling knowledge and consistent action.

2. Gamification, Behaviour Change, and Engagement in Recycling Systems

Education for Sustainable Development (ESD), as defined by UNESCO, aims to equip learners with the knowledge, skills, values, and attitudes necessary to make informed decisions and take responsible actions for environmental integrity, economic viability, and social equity, both for present and future generations (UNESCO, 2020). Digital strategies especially gamification, play a critical role in transforming passive awareness into sustained recycling behaviour by combining informational support with motivational mechanisms. In the following chapters the conceptual basis of our work is laid.

2.1 Conceptual Foundations: Gamification, Serious Games, and Behaviour Change Approaches

Gamification has become an established approach for enhancing user engagement and activating sustainable behaviours. It applies game-design elements such as points, badges, challenges, feedback loops, and leaderboards in non-game contexts to increase engagement and behavioural persistence (Deterding et al., 2011). In sustainability education, gamification has demonstrated measurable effects on learning retention, behavioural activation, and habit formation (Hoffmann and Pfeiffer, 2021; Novo et al., 2024) It can be implemented across multiple layers of design, including surface-level interface elements, underlying game mechanics, heuristic principles for user interaction, and deeper conceptual frameworks that guide system behaviour (Deterding et al., 2011). In sustainability education, gamification bridges the gap between environmental knowledge and consistent behavioural application. Hoffmann and Pfeiffer (2021) found that scenario-based challenges, iterative feedback, and reinforcement improved waste-sorting knowledge retention and the real-world application of sorting rules (Hoffmann and Pfeiffer, 2021). These results show that solutions with motivational design enhance not only cognitive understanding but also lead to behavioural changes. Closely related to gamification are serious games. These represent fully developed game environments created for educational, behavioural, or training purposes. As Bopp (2009) outlines, serious games can be categorised into educational, health, corporate training, and persuasive games, depending on their thematic objectives and targeted outcomes (Bopp, 2009). In sustainability contexts, serious games allow users for instance to engage with simulated decision-making scenarios and experience the environmental consequences of their choices within risk-free, immersive settings (Dudok and Pigniczki-Kovács, 2024). Such simulations support experimental learning, often facilitate a deeper understanding of complex environmental systems and trigger behavioural changes. Behaviour change strategies in sustainability education are based on psychological theories that explain human motivation and action. Self-Determination Theory identifies autonomy, competence, and social relatedness as fundamental psychological needs for intrinsic motivation and long-term engagement (Deci and Ryan, 1985). This theory has been applied in environmental contexts to guide the design of interventions that encourage sustainable behaviour through intrinsic triggers rather than external enforcement. Thus, Hsu developed a framework with key behavioural triggers such as challenge, feedback, perceived impact, and reward mechanisms to maintain user attention and commitment in environmental settings (Hsu, 2025). By aligning game design with motivational theory, Hsu's work offers an evidence-based structure for developing gamified sustainability interventions that go beyond surface engagement to support lasting behavioural change.

2.2 Behavioural Engagement Strategies in Sustainability Education

Effective recycling education integrates knowledge transfer with motivational feedback and scalable digital learning environments for flexible, individualized learning in daily life (Rof, Bikfalvi and Marques, 2024). In digital learning environments gamification plays a vital role (Timlett and Williams, 2008b; Konstantinidou *et al.*, 2024; Hoffmann and Pfeiffer, 2021). Social mechanisms like leaderboards and community challenges foster shared responsibility and enhance participation in recycling systems (Briones et al., 2018). Projects like GoBeEco demonstrate how gamified elements combined with real-world actions improve sustainable behaviour (Novo et al., 2024). Timlett and Williams emphasise that the most effective recycling tools combine educational content, personalised feedback, challenge progression, and local adaptability (Timlett and Williams, 2008b).

2.3 Overview on Existing Digital Solutions for Recycling Engagement

Numerous digital initiatives have been exploring the potential of gamification and behavioural engagement strategies to encourage sustainable practices and participation in recycling. However, most focus on isolated engagement aspects rather than offering an integrated platform. The GoBeEco project for instance used gamification for general sustainability habits (Novo et al., 2024) but lacked operational recycling guidance. RecycleMich, an Austrian recycling app, was developed to assist users in correctly separating plastic, metal, and beverage carton packaging in accordance with European recycling targets. RecycleMich incorporates barcode scanning recycling challenges and offers discounts or vouchers for sustainable behaviour (Denovo · RecycleMich App, no date). Nevertheless, its educational dimension remains limited. In contrast, apps like JouleBug promote sustainable behaviours through social competitions, digital rewards, eco-friendly challenges and rewards (Make Sustainability Second Nature - JouleBug, no date) but lacks localised recycling guidance. The TerraCycle-system as another example enables recycling of hard-to-recycle materials via mail-in programs (Wikipedia contributors, 2025), but its digital engagement focuses on logistics rather than daily behaviours. Sensoneo delivers smart waste management solutions for municipalities, focusing on real-time bin monitoring, waste tracking, and collection route optimisation (Smart Waste Management Company | SENSONEO, no date). Although the platform enhances waste system efficiency on a municipal scale, its citizen-facing engagement features are minimal, lacking gamification or educational modules to foster recycling literacy and sustained behavioural change. While each project demonstrates strengths, there remains a gap for solutions combining modular learning, real-time behaviour tracking, personalised feedback, and gamified engagement within one platform. A novel solution shall overcome this gap by offering structured educational modules, challenge-based participation, real-time feedback, and sustainability rewards, translating behaviour change theories into a coherent digital intervention. By aligning educational content with behaviourally supportive game mechanics, the Transformers-App offers a novel contribution to digital sustainability education, supporting users in translating knowledge into consistent and measurable recycling action.

3. Research Approach and Participatory Development

In this research, a Design Science Research (DSR) methodology was used to guide the development and evaluation of the Transformers-App, a digital gamification solution to promote sustainable recycling engagement and behaviour change. DSR has been chosen for its systematic approach for solving real-world problems through the creation and evaluation of innovative artefacts particularly in complex socio-technical contexts where theory-driven design and iterative stakeholder feedback are essential (Hevner and T. March, 2004). The Transformers-App operates at the intersection of behavioural science, digital sustainability education, and user-centred interface design aligning with DSR's objective of producing practically relevant and rigorously evaluated solutions (vom Brocke, Hevner and Maedche, 2020). The methodology facilitated an iterative refinement of the app in response to real-world user feedback while contributing to the broader scientific understanding of digital behavioural intervention. Applying the DSR process allowed the project to systematically address key behavioural barriers in recycling through the design, testing, and improvement of an educational and motivational app. The research followed four main phases: (1) Problem exploration and state-of-the-art analysis, (2) Expert interviews and participatory stakeholder engagement, (3) Co-design sprint and student involvement, and (4) evaluation and usability testing.

3.1 Problem Exploration and State-of-the-Art Conclusions

The research began by exploring behavioural barriers in recycling participation and identifying effective design strategies in sustainability education. A literature review was conducted to analyse existing research on behavioural engagement strategies, gamification approaches, and recycling practices. The most promising analysis results for supporting behaviour change were beside feedback loops, rewards and scenario-based learning (Deterding et al., 2011; Hoffmann and Pfeiffer, 2021) serious games to foster experiential learning and reflection (Bopp, 2009). In the conceptual design of the app, we also emphasised the importance of motivational triggers and personalised engagement (Hsu, 2025). The analysis of existing recycling engagement projects came to the main result that most of the projects lacked an integration of modular learning, real-time behaviour tracking, and user-centred feedback mechanisms. These gaps shaped the conceptualisation of the Transformers-App as a holistic platform combining education, feedback, challenge engagement, and behavioural analytics. Our approach focuses on translating theoretical insights from gamification and behaviour change research into a participatory digital intervention for recycling engagement.

3.2 Expert Interviews and Participatory Stakeholder Engagement

To align the app development with practical needs, in a second research phase semi-structured expert interviews were conducted with municipal waste representatives and stakeholders from recycling industry. The results of the first phase were incorporated into this phase and thus discussions focused on operational challenges in waste management, user behaviour barriers in recycling participation, specific problems related to plastic waste, and digital opportunities for behavioural support. Experts highlighted that beside user confusion due to regional variation sorting rules, a lack of feedback on recycling behaviour and missing personalized support can be seen as the main factors contributing to sorting errors and disengagement. Motivational systems were seen as insufficient, especially for international users unfamiliar with local recycling practices. Plastic waste management emerged as a major concern exacerbated by contamination and mixed materials. Experts highlighted the need for digital solutions offering targeted guidance, feedback, and real-time support. Further on they emphasized that user-centred tools should combine education with real-time behavioural reinforcement to improve recycling outcomes. The experts' findings were used as input in a half-day co-design sprint with 10 participants, comprising municipal partners, UX designers, recycling experts and scientific researchers, to develop a first design concept. The sprint was based on the design sprint by Knapp et al. (2016). The original two-day group work phase was shortened to half a working day to save time, as the workshop participants were volunteers who did not receive any financial compensation. Results of the sprint included several aspects: camera-based identification of materials, explanation of material separation and presentation of the results/effect of correct collection/separation.

3.3 Student Involvement in App Development and Evaluation

In a third phase master's students of computer science participated in two ways. First, through the co-design sprint in an early stage of the project. From a user perspective they identified requirements and generated innovative ideas. In a later phase students project groups developed digital recycling-related prototypes (e.g. an informative campus-oriented app prototype combining recycling guidance with campus services like Mensa menus, course schedules or a waste-bin sorting smartphone game). Although not directly interrelated with Transformers-App development, these projects provided valuable insights into user engagement, interface design, and gamified educational strategies. For instance, it has been demonstrated that recycling can be communicated in a more subtle way through a visually sophisticated mobile sorting game with engaging gameplay, rather than through text-based knowledge transfer.

3.4 Evaluation

Project results were evaluated in group workshops and individual sessions. One municipal waste representative and four stakeholders from recycling industry tested core features such as onboarding, challenge-based participation, progress dashboard, and educational modules. Feedback focused on usability, clarity, content relevance, and motivational mechanisms. In particular, experts discussed data protection aspects (e.g. clear names and activity tracking) and the question of whether there should be a difference in user motivation between non-profit and commercially collected materials. Continuous expert input ensured the app met user needs, improving its support for recycling behaviour.

4. Transformers-App: A Gamified Platform for Behavioural Changes in Recycling Processes

Building on the theoretical foundations outlined in Chapter 2, the app integrates key behavioural strategies such as motivational triggers, challenge-based engagement, feedback mechanisms, and social incentives. The app’s architecture was designed to overcome limitations identified in existing recycling applications, including the lack of integrated educational content, minimal operational guidance, and absence of personalised feedback. This chapter presents the conceptual motivations, technical features, and modular infrastructure of the app, highlighting how it translates state-of-the-art knowledge into applied behavioural change design.

4.1 Conceptual Foundations and Design Motivation

The Transformers-App was developed to address behavioural barriers in recycling through gamification, participatory design, and modular education. The app’s design is grounded in Self-Determination Theory (L. Deci and M. Ryan, 1985), embedding autonomy is supported through user-defined goals, competence via feedback and progress dashboards, and relatedness through leaderboards and community challenges. These principles combined with behavioural triggers from Chapter 2, guided the functional development.

4.2 Gamified Architecture and Core Interface

The Transformers-App is structured around a personalised progress dashboard. While users do not receive an immediate overview upon logging in, the dashboard becomes the central space for tracking recycling-related activities once engagement begins. As shown in Figure 1, the interface provides access to the user's accumulated points, weekly activity, current level, progress graphs, material distribution charts, and a community leaderboard. These metrics are also used on the homepage. To support the onboarding and initial engagement process, a dedicated help icon is accessible from the dashboard, which leads to an introductory section explaining the purpose and key features of the app to guide users in a transparent and accessible manner. Points are earned by completing challenges, engaging with educational modules, and scanning recyclable items (via packaging barcodes). Scanned items are matched with public databases to determine the material and product information for the metrics. Users can also adjust the information (e. g. material, weight) themselves. Accumulated points contribute to level progression, reinforcing participation and recognising effort. In contrast to existing solutions (Section 2.3), which focus on badges, Transformers emphasises tracking of cumulative performance to encourage ongoing engagement. The dashboard features visual feedback tools such as a weekly activity and material distribution chart to help users to contextualise their recycling efforts within a broader sustainability framework. These tools support effective learning and encourage sustainable changes in recycling behaviour. The leaderboard encourages social comparison and collective engagement by ranking users based on their recycling activities. This drives long-term motivation by encouraging shared responsibility and constructive competition. By combining the tracking of personal progress with visibility in the community, the dashboard supports both self-regulated behaviour and social interaction in a gamified system.

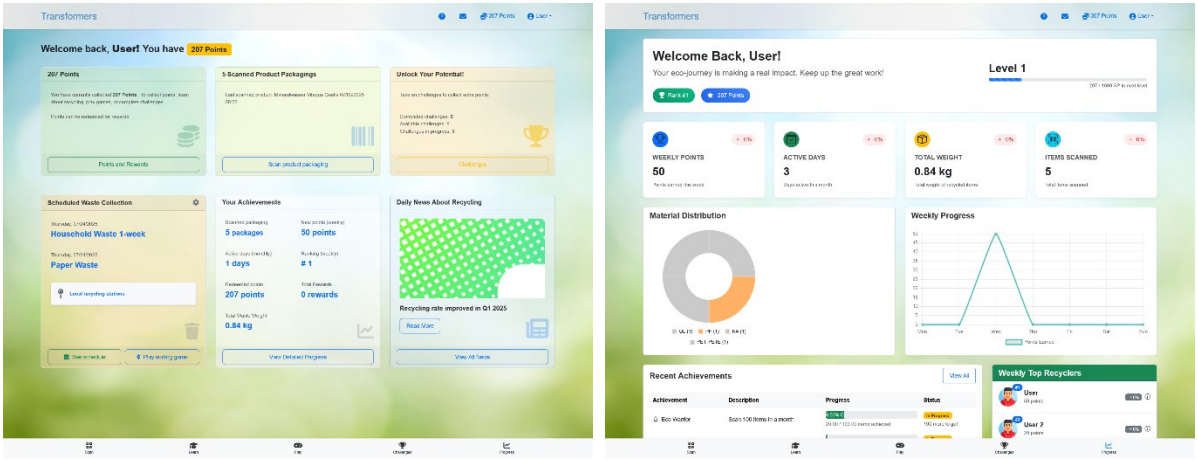

Figure 1: Transformers-App Home (left) and Progress Dashboard (right) with user rank, recycling data, achievements, leaderboard, and engagement metrics

4.3 Educational Integration and Learning Flow

A key feature of the Transformers-App is the educational component, which aims to close knowledge gaps through interactive micro-learning modules (Figure 2). These modules cover topics such as waste sorting, e-waste disposal and common household sorting mistakes and combine clear objectives with scenario-based stories. Each module ends with a short quiz that reinforces learning through immediate feedback and encourages the application of recycling behaviour in real life. External resources from organisations such as the European Commission and Recolight lend credibility to the content, while the Eco Games Hub supports further practice through interactive sorting games. The app ensures that learning outcomes are translated into measurable recycling actions by embedding modular learning into a game-based system, encouraging long-term sustainable habits. For example, the learning modules communicate information on separating materials or misthrows, which in turn improves performance in sorting games and collection challenges.

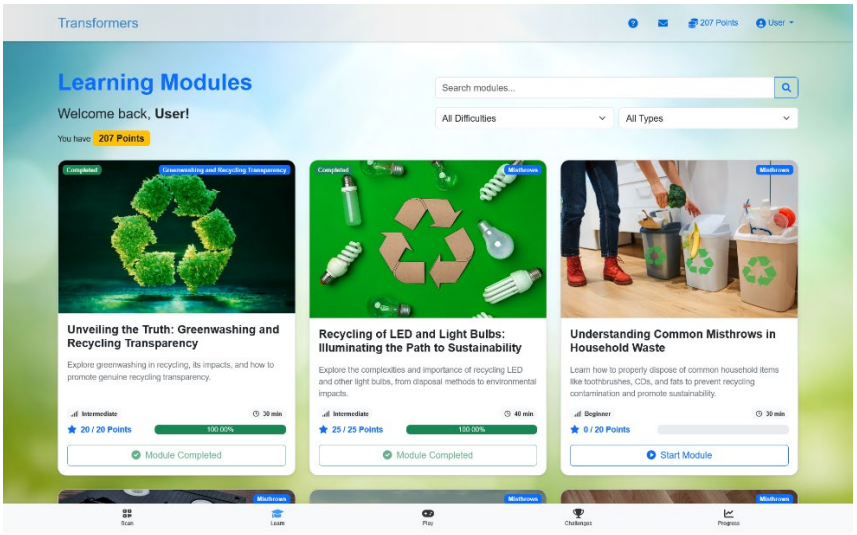

Figure 2: Learning module introduction page outlining key objectives and trusted resources

4.4 Challenges and Motivational Progression

The developed solution features a progressive challenge system designed to activate and sustain recycling behaviours. These challenges are structured around specific, measurable goals, beginning with simple tasks like scanning recyclables items and advancing to more complex tasks such as weekly plastic consumption challenges. Each challenge is time-bound to maintain momentum and follows an incremental difficulty structure, allowing users to gradually build recycling habits through achievable milestones. This progression logic draws on behaviour change strategies discussed in Section 2.2, which emphasise the importance of reinforcement through incremental achievements. Successful challenge completion contributes to multiple engagement layers: users receive points, digital badges, leaderboard advancement, and access to exclusive rewards. These multi-layered incentives foster motivation by recognising both short-term efforts and long-term behavioural commitment. A distinctive feature of the system is its flexibility: external partners, such as municipalities and companies, are encouraged to design and publish their own challenges, allowing the app to be tailored to local recycling needs and sustainability goals. This adaptability allows the app to tailor content to local recycling rules, community needs, and sustainability initiatives. By linking individual participation to broader collective efforts, the app transforms recycling from a routine task into a goal-driven and habit-forming civic engagement activity.

4.5 Social Incentives and Tangible Rewards

The Transformers-App integrates social incentives and a modular reward system to connect digital engagement with real-world sustainability outcomes. A community leaderboard promotes social comparison, recognition, and shared environmental responsibility. Furthermore, users can accumulate points, which can be redeemed to rewards. The user-friendly rewards interface helps users to track progress and recognise the environmental value of their actions. In the participatory design workshop, we developed conceptual reward ideas including custom 3D-printed items with environmental impact certificates, access to recycling seminars and workshops, and local events with sponsored gifts. Participants discussed the possibility of enabling external partners sponsoring challenges or offering branded rewards. Though conceptual, this flexible reward structure demonstrates the app's potential to scale partnerships and engage diverse stakeholders in sustainability campaigns. By combining digital recognition, tangible rewards, and scalable partnerships, the app fosters sustained, community-driven recycling behaviours.

4.6 Technical Infrastructure and Analytics Architecture

Transformers technical infrastructure is a modular, scalable system designed for adaptability and integration with recycling and sustainability initiatives. It showcases core engagement mechanisms while supporting future expansion. The architecture comprises three main layers: user interface, application logic, analytics/administration layer. These layers interact via defined interfaces, ensuring modularity. Components like the educational module and the reward mechanism can be adapted for other platforms without major changes. The frontend, built with Bootstrap, offers a responsive, device-independent interface with personalised progress tracking, educational content, and community features adaptable to diverse audiences. The backend, implemented with Node.js, manages user interactions in an event-driven environment, with Firebase enabling

real-time data handling, authentication, and cloud-based database services. The analytics layer supports personalised feedback, and behaviour monitoring, while an administration dashboard allows system administrators to create and configure challenges, monitor engagement, and adjust educational content based on behavioural data. Hosted on Microsoft Azure, the system ensures reliability and scalability. This modular prototype provides a flexible foundation for behavioural change across varied settings supporting future enhancements like AI-driven personalization, predictive analytics, and adaptive learning, and integration into broader sustainability ecosystems.

5. Artificial Intelligence for Smart Recycling Guidance

The future integration of Artificial Intelligence (AI) can enhance the recycling app that provides real-time recycling statistics, visual feedback, and gamified learning modules in a variety of ways. This is summarised in the following figure:

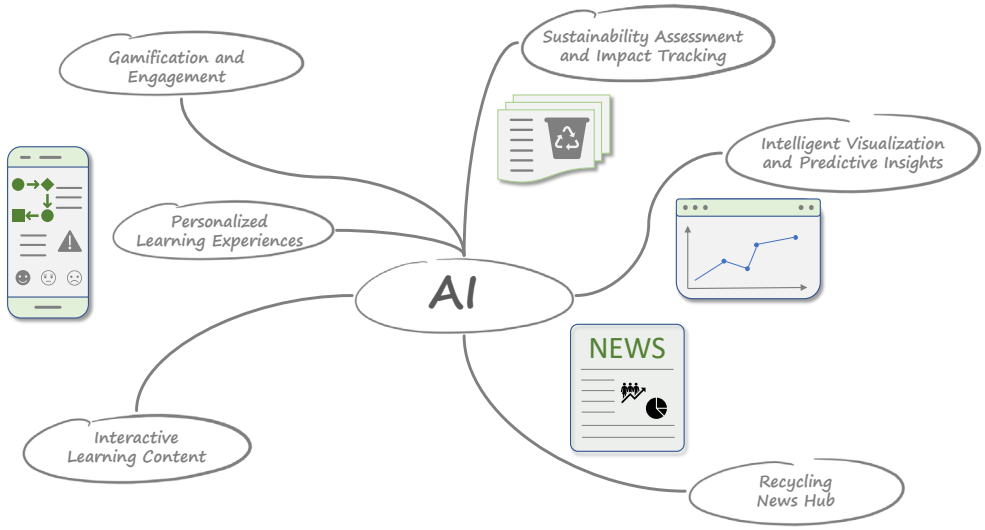

Figure 3: Integrating Artificial Intelligence for Smart Recycling Guidance

By analysing user behavior, the integration of AI enables the creation of personal learning paths. The selection and content of different modules can be customized to the individual user by using AI, guiding them on their individual learning path. AI can support users to design the learning path individually and interactively: the users are motivated to change their behaviour through customized goals and levels of the game-based tasks which are generated individually for them. Balanced feedback e.g. suggestions or predictions helps to achieve this (see e.g. Sajja et al., 2024). AI-generated analyses of individual learning progress and the consequences of users' recycling behaviour help users to adapt their behaviour where necessary (see e.g. Yayzy Footprint Calculator) and make it possible to calculate and visualize the individual impact of users' behaviour on the environment. This makes it very clear to users how useful it is to engage in recycling and thus support the goals of the circular economy. AI can thus play the role of a virtual and personal tutor that provides feedback in real time, interacts with the user, generates customized learning content, offers tips and tricks and motivates the user, e.g. through quizzes (see also Chen et al., 2023; Goel, 2020). Natural language processing (NLP) can summarize the latest recycling news, allowing users to quickly access information and better understand recycling habits and their impact. Future AI integration in the Transformers app will offer personalized learning, enhanced engagement through games and quizzes, and insights into user behaviour impact.

6. Discussion

The evaluation of the project results combined expert workshops and usability testing, providing comprehensive insights into its effectiveness in fostering recycling engagement. Experts from municipal waste management, recycling companies, and sustainability education institutions participated in structured feedback sessions. These sessions assessed app clarity, behavioural guidance mechanisms, and the motivational logic of gamified challenges. Feedback highlighted strengths such as real-time feedback integration, challenge-based engagement, and adaptive support for diverse user profiles. The app's gamified structure — point systems, progress tracking, and community leaderboards — was perceived effective in initiating and reinforcing behavioural changes. Experts highlighted the flexibility of the challenge system and the role of analytics in enabling personalised feedback and behavioural reflection. Whereas the overall evaluation was successful, some

improvement suggestions concerning clarity, the quality of feedback messages, and an enhanced visual presentation of behaviour tracking were made. A major strength of the research was its participatory development methodology, ensuring iterative improvement based on both institutional expertise and user perspectives. However, limitations must be acknowledged: testing occurred primarily within a university setting among users already interested in environmental issues. Broader evaluations are necessary to assess adaptability and long-term impact across diverse demographic and infrastructural contexts. Overall, our findings affirm that gamified digital tools can bridge the gap between environmental knowledge and consistent behaviour, particularly when supported by interactive feedback and community engagement. Future work should explore how localised content, adaptive learning paths, and cross-sector partnerships can strengthen behavioural outcomes. As a modular platform, the developed solution presents a promising basis for scalable, collaborative recycling education within the circular economy transition.

7. Conclusion and Path Forward

This research addressed the challenge of promoting correct recycling behaviour through digital solutions that integrate education, motivation, and engagement. Within the framework of ESD, the study demonstrated how gamification and interactive learning can support behavioural change and foster sustainable practices in everyday life. The development of the Transformers-App offered valuable insights into translating recycling knowledge into measurable action through a user-centred design approach. It contributes to the field of digital sustainability education by combining structured learning modules, challenge-based engagement, and personalised feedback mechanisms. Developed through a participatory process, the app addresses key barriers such as sorting complexity, lack of guidance, and low motivation. By embedding behavioural theory into gamified strategies, the app illustrates how digital tools can bridge the gap between environmental awareness and consistent action. Building on this foundation, future research should explore the app's adaptability across diverse infrastructural contexts and evaluate its long-term behavioural impact. Emphasis should be placed on pilot testing to assess usability and effectiveness in different scenarios and conditions. Moreover, future development can benefit from integrating AI-driven personalisation, municipal system interoperability, and deeper social networking features.

Ethics Declaration: The ethical clearance was not required for the research.

AI Usage Declaration: No AI tools were used in the development the Transformers-App. For the paper, AI-based tools were minimally employed to paraphrase or enhance the wording of some sentences, but they did not contribute to the overall content creation, data analysis, or structure. All core intellectual contributions were human-driven, and AI use was limited to minor stylistic improvements.

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