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Progressive web applications as a tool to achieve SDG 4 and SDG 8: Evidence from vocational schools in marginalized regions

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Abstract

Ensuring equitable vocational education in remote areas remains challenging due to limited infrastructure, unstable connectivity, and shortages of qualified teachers. This study examines the implementation of a Progressive Web App (PWA)–based learning ecosystem to enhance learning access, competency development, and employability outcomes in seven vocational schools across Pulau Sumba, one of Indonesia's least developed regions. A proprietary platform (https://www.pwa-smk.id/) integrating an Academic Information System, e-learning, and internship (Prakerin) management was developed with offline-first caching, low-bandwidth microlearning, and cross-device accessibility. Using an explanatory sequential mixed-methods design, the quantitative phase involved 214 students, followed by qualitative data from 32 purposively selected teachers and school managers, complemented by system-generated engagement logs. Ethical approval was obtained from Universitas Negeri Yogyakarta (No. B/2795/UN34.21.LS.17/LT/2025). The results demonstrate substantial improvements in learning access, vocational and digital skills, and user engagement. Online learning access increased from 46.2% to 87.9%, with 68.1% of materials accessed offline. Pre- and post-assessments showed gains in hard skills (31.1%), soft skills (31.6%), digital literacy (46.7%), and certification readiness (47.0%). The intervention contributed to multiple SDGs, including quality education, youth employability, reduced inequalities, and sustainable practices. Community spillover effects included increased parental involvement, MSME engagement, and digital literacy uptake. Overall, the findings provide strong empirical evidence that context-adapted PWA solutions offer a cost-effective and inclusive approach to accelerating vocational education and community transformation in remote areas.

Keywords: Digital inclusion, Employability skills, Offline-first learning, Progressive web application, Remote and marginalized regions, Sustainable development goals, Vocational education and training.

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Contents

Contribution of this paper to the literature

This study provides the first large-scale empirical evidence of an offline-first PWA ecosystem fully integrated into vocational school operations in marginalized regions. Unlike prior EdTech studies, it simultaneously quantifies learning access, competency gains, multi-SDG impacts, and community spillover effects, demonstrating PWA as a systemic catalyst for equitable TVET and sustainable development.

1. Introduction

The attainment of Sustainable Development Goal (SDG) 4 on quality education, alongside SDG 8 on decent work and economic growth, remains a recurring challenge in marginalized and remote areas with shortages of learning resources and trained teachers. Technical and Vocational Education and Training (TVET) has been recognized as a means of strategically addressing such disparities; however, participation and access vary (Alla-Mensah, Henderson, & McGrath, 2021; Plance, 2020). Recent evidence suggests that education, specifically TVET and skills-based work, is a key driver of poverty reduction and sustainable development outcomes for young people in poor contexts (Zhang, 2024). Yet, societal barriers including unreliable infrastructure, low adoption of technology and inadequate curriculums linked to sustainability frameworks still seem to slow down the pace for reaching SDG targets (Pham & Håkansson Lindqvist, 2025; Vladimirova & Le Blanc, 2015).

Figure 1. SDG 4 (Quality Education) and SDG 8 (Decent Work and Economic Growth) as the core framework guiding the digital transformation of vocational education in marginalized regions.

Figure 1 illustrates the conceptual focus of this study on SDG 4 (Quality Education) and SDG 8 (Decent Work and Economic Growth). These two goals are central to the framework of this research, as they directly relate to improving access to quality learning and enhancing employability outcomes in vocational education. SDG 4 emphasizes inclusive and equitable quality education, while SDG 8 highlights the development of skills relevant to employment and economic participation. The visualization highlights how the PWA-based intervention is positioned to support both educational quality and workforce readiness in marginalized regions. To respond to these challenges, digital innovations have increasingly become necessary. Research indicates the capacity of online learning ecosystems like MOOCs as enabler for SDG 4 to increase access, convenience and inclusivity (Islam, Akter, & Knezevic, 2019). Larger paradigm shifts in education due to digitization also work towards speeding up SDG realization as they provide more flexible, inclusive and knowledge-centric modes of education (Maheshkar, Kapse, Bhattacharjee, Poulose, & Sharma, 2024; SM, 2025). In the area of vocational education, new technologies such as AI have been demonstrated to improve skilling pathways and labor-market matching leading directly to SDG 4 and 8 (Prasetya et al., 2025). They are part of a larger trend toward reconceptualizing education systems as the means to generate workforces adaptable to quickly transforming economies (Fung & Hosseini, 2023).

Despite such progress, technological and technology-enabled solutions need to be designed for implementation in low-resource settings, particularly where connectivity, device performance and digital literacy are deterrents. PWAs offer a potential solution to this problem. PWAs can offer reliable, fast and appealing user experiences by bringing together the ease of access of web applications with the power of native apps that perform well under restricted connectivity (Hajian, 2019; Hume, 2017). There are studies where PWAs were considered to be the viable solution for bringing together cross-unit/cross-device application development and a cost-effective approach (Biørn-Hansen, Majchrzak, & Grønli, 2017), and even

their effectiveness was measured in a systematic way using multi-criteria decision models such as Analytic Hierarchy Process (Khan, Al-Badi, & Al-Kindi, 2019). In light of the convergence between the imperative to scale vocational educational access and capabilities offered by PWAs for extremely resource constrained environments, there is a critical need to understand how PWAs can work as an intervention solution in advancing SDG 4 and SDG 8-related sustainable development initiatives. While the literature would state that technology plays an important role in quality education and sustainable development (Saini, Sengupta, Singh, Singh, & Singh, 2023), there are few studies providing direct evidence on PWAs integration within vocational school ecosystems, especially so for geographically disadvantaged areas.

Closing this gap, we investigate the deployment of a PWA designed to facilitate teaching, learning, and skills assessment in marginalized vocational schools. By examining impact, usability, and relevance to educational and economic outcomes, this research enhances understanding of how PWAs can operationalize the principles underpinning SDG 4 and SDG 8, offering practical and policy implications for scaling equitable VET.

2. Method

2.1. Research Design

The study employs a mixed-methods explanatory sequential design to explore the effectiveness of a PWA in empowering vocational education and promoting SDG 4 (quality education) and 8 (vocational training and economic growth) in resource-marginalized areas. Mixed-methods strategies are particularly useful in exploring complex relationship dynamics among technology adoption, educational access and opportunities, and socioeconomic barriers, which are widely discussed in the literature on digital inclusion and rural development (Kyrylov et al., 2024; Otieno, Kaye, & Mbugua, 2023). The quantitative phase focused on the quantification of changes related to learning outcomes, engagement and ease of use, while in the qualitative phase we explored experiences and socio-structural constraints that impact on the technology effectiveness in a marginalized community, which are discussed analysis, these findings are closely aligned with research advocating for context-aware interventions for marginalized population (Mir et al., 2020; Moazzem & Shibly, 2020; Ticona et al., 2025).

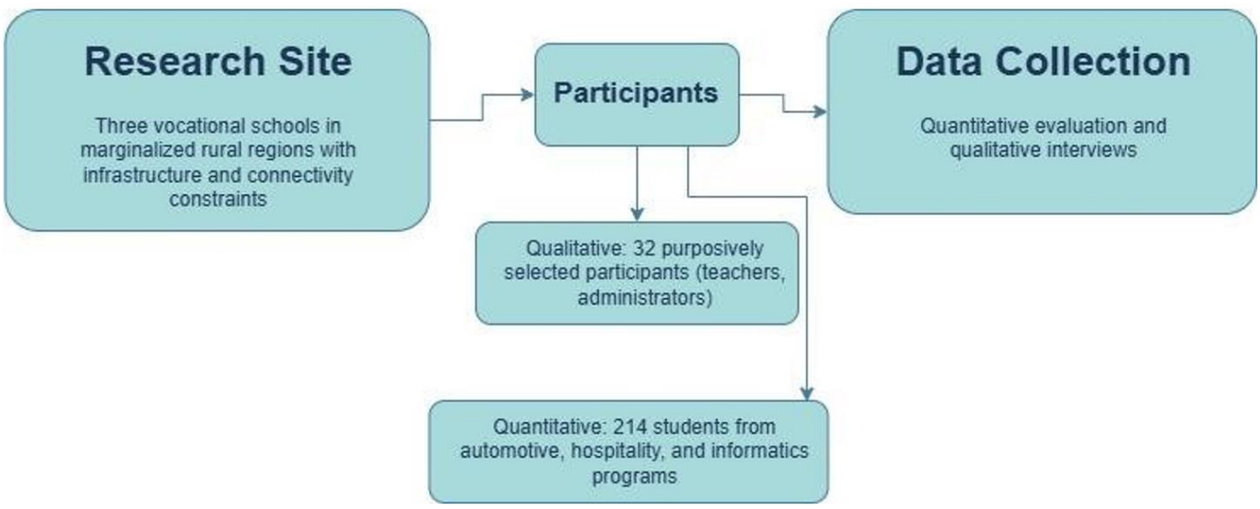

Figure 2. Research site, participants, and data collection.

2.2. Research Setting and Participants

Figure 2 presents the research setting consisting of seven vocational schools in the marginalized remote areas around Sumba Island, which are known for their poor internet access, a lack of public facilities and socio-economic vulnerability. These are common hurdles that disadvantaged areas in Indonesia and other developing countries must overcome (Basabe & Galigao, 2024; Edwards, Asadullah, & Webb, 2024) access to digital technologies, educational equity and access to labor-market opportunities. These settings oftentimes endure constrained public services and glaring educational disparities as evident by past research examining technology discrepancies in rural areas (Bandyopadhyay, Bardhan, Dey, & Bhattacharyya, 2021). The PWA system implementation at these seven schools is also a representative sample of the wider installation using the systems. In the quantitative study, 214 VET students participated from three different prominent skill pathways: automotive, hospitality, and informatics that are related to the labour market needs targeted by SDG 8. Eighteen teachers and 12 principals also participated in the qualitative part of the study. We conducted semi-structured interviews with 32 participants and used purposeful sampling for diverse representation, including individuals experiencing gendered challenges, digital literacy challenges, and from varying socio-economic backgrounds. This sampling strategy aligns with extant global findings, emphasizing the need to consider equity and inclusion when leveraging digital learning interventions (Alshraah, Alawawdeh, Issa, & Alshatnawi, 2024; Hassan & Anees, 2024).

2.3. Intervention: Progressive Web Application

The PWA intervention was built with an offline-first approach, including service workers, caching approaches and lightweight assets so that it remains operative in low-connectivity scenarios – a key need for digital interventions in LMIC (Kyrylov et al., 2024; Ogundipe, Sampson, Bakare, Oketola, & Folorunso, 2022). The design was informed by PWA development best practices such as performance optimization, reducing code complexity, and cross-platform accessibility (Domes, 2017; Johannsen, 2018). For energy savings and low-level device utilization, UI and resource management strategies drew on empirical comparisons of PWA

performance (Huber, Demetz, & Felderer, 2021). Key features included: a). Competency-based learning modules, b). On the other hand, microlearning contents tailored for rural bandwidth constraints, c). Offline assessment capabilities, d). Teacher dashboards, e). Learning logs and analytics.

Figure 3. Core components of Progressive Web Application technology.

Figure 3 illustrates the core architectural elements of a PWA, below which are listed: The Application Shell Architecture, the secure HTTPS protocol, the Service Worker, and Web App Manifest. These are designed to give you a good head start in terms of fast load times, data integrity, offline access, and installability on the device. It illustrates how such characteristics make PWAs well-suited for a school-vocational environment with low connectivity, where students and teachers can have constant access to course resources even from unstable networks. This fits into research which views digital transformation as a major enabler of inclusive and sustainable education (Danladi, Prasad, Modibbo, Ahmadi, & Ghasemi, 2023; Vela-Jiménez, Sianes, López-Montero, & Delgado-Baena, 2022).

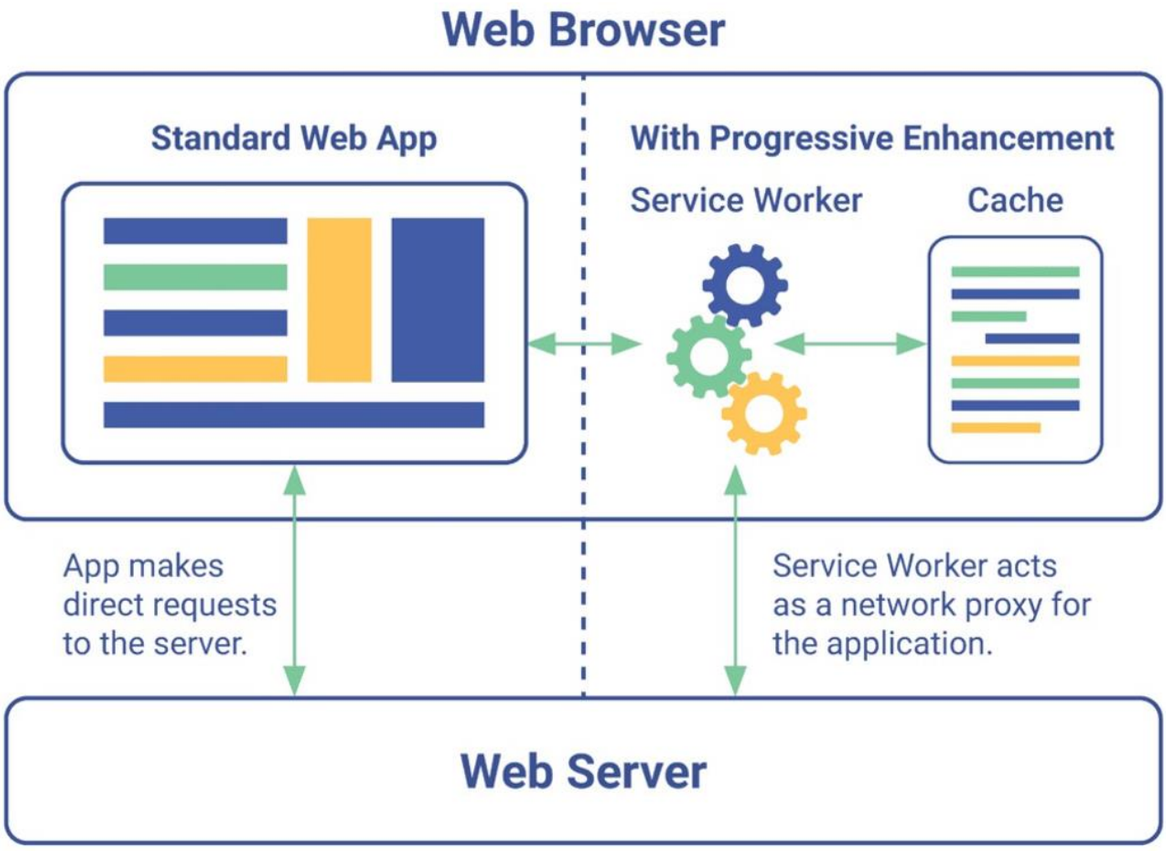

Figure 4. Architectural comparison between standard web applications and PWAs.

The architecture of a traditional web application and PWA are contrasted in Figure 4. Whereas a classic web application communicates directly with the server, even if it uses push notifications and background sync in an attempt to emulate offline behavior, the PWA generation adds a Service Worker layer as a network proxy (between your app and the internet) that gives you programmatic control of caching, routing requests to the server, or serving them from local storage, background syncs while the browser is not running. This architecture brings PWAs the capability to ensure reliable access despite flaky or expensive connectivity, which is particularly beneficial in learning environments located in remote/geographical areas.

2.4. Instruments

2.4.1. Competency Assessment

National competency instruments developed and validated by experts were used to develop a pre-test and post-test instrument. This approach is consistent with demands to bolster human capital and employability through skills measurement (Ticona et al., 2025). Development process that each test item reflected the domains of core competencies needed for successful occupational training, such as technical and soft skills facilitating the assessment's accurate measurement of students' initial abilities and learning gains after intervention. Validity and content validity were further supported by expert validation, as well as alignment with curriculum standards, relevance of content, and clarity of indicators. This method not only enhances the robustness of rating but also enables evidence-based decisions to be made for vocational programs aiming to improve labour market readiness and industry relevance.

2.4.2. Learning Analytics

The PWA also recorded engagement instruments (e.g., session logs, task completion, etc.) for addressing digital inclusion studies, highlighting the use of analytics to track equal participation (Otieno et al., 2023). These analytics revealed fine-grained details of student engagement patterns when engaging with learning materials under different connectivity conditions, and consequently, the types of usage patterns, participation gaps, and challenges that learners in marginalized regions might experience. By monitoring both types of activity, the system also provided a detailed picture of learning behavior, showing which modules were visited most often, how close students came to completing tasks, and how much offline feature use occurred. These data are crucial for guiding adaptive instructional decisions and customizing supports for low-engagement learners, ensuring that educational technology interventions remain inclusive, evidence-based, and responsive to students' real-world constraints.

2.4.3. Usability Evaluation

Usability was evaluated using the PWA Usability Heuristics (PWAUH) model (Anuar & Othman, 2024) in addition to the traditional SUS measurements. This twofold characterization makes it possible to evaluate both general usability and PWA-specific interaction elements. The PWAUH framework allowed for a laser-focused analysis of the diabetes app, focusing on those elements unique to Progressive Web Applications (and fostered by PWAs) that were not measured as part of the SUS, such as offline functionality, device responsiveness, caching, and installability, whilst introducing a broader measure that took into account perceived ease of use and efficiency. By including both of these instruments, the investigation was able to gain a greater understanding of overall user experience, determining possible interface difficulties, navigation problems, or issues needing design revision. The rigorous usability testing was critical to verify that the PWA works in a challenged environment and fulfills the needs of users in vocational education (students and teachers).

2.4.4. Semi-Structured Interviews

Interviews addressed learners' perceptions of accessibility, equity, empowerment, and relevance to employability dimensions highlighted in literature connecting digital solutions with SDG progress (Alshraah et al., 2024; Basabe & Galigao, 2024; Ogundipe et al., 2022).

2.5. Data Collection Procedures

Data collection took place in three iterative phases.

a) Baseline Phase

Preliminary forms (demographic, digital literacy surveys, and initial competencies pre- tests) were issued to the participants based on an appreciation of issues around prior context knowledge among underprivileged youth (Moazzem & Shibly, 2020).

b) AO Phase (8 weeks)

Difficulty of required modules and assessments were done through PWA. Online and offline logs of interactions were automatically logged.

c) Transition (After-Intervention) Stage

Post-tests, usability questionnaires and interviews were conducted on learning equity, empowerment and perceived employability.

Procedures were consistent with ethical standards and inclusion-minded forms of technology integration as highlighted in educational equity frameworks (Otieno et al., 2023).

2.6. Data Analysis

2.6.1. Quantitative Analysis

- Competency gains were statistically verified by paired-sample t-tests.
- Effect sizes were quantified using Cohen's d.
- Sensibility, usability (PWAUH + SUS), and reliability values were assessed using descriptive statistics.

Learning analytics were analyzed to determine patterns of use, offline dependence, and differences in engagement a method used by studies of social technologies as intermediaries for the digital divide (Bandyopadhyay et al., 2021).

2.6.2. Qualitative Analysis

Interview transcripts were analyzed thematically, with emphasis on dimensions of equity and access, inclusivity in terms of gender, learning empowerment and employability: issues identified as significant to discussions on the successful implementation of SDGs (Hassan & Anees, 2024; Mir et al., 2020; Vela-Jiménez et al., 2022).

2.7. Integration of Findings

Quantitative and qualitative results were cross-referenced during interpretation to understand the contribution of PWAs across larger systemic and socio-economic domains. This integration is grounded in approaches to digital inclusion and multi-dimensional analysis of the SDGs (Danladi et al., 2023; Dolley et al., 2020).

2.8. Ethical Considerations

This implementation is formally validated and ethically approved, as evidenced by the official *research permit and ethical clearance* issued by Universitas Negeri Yogyakarta, with document number B/2795/UN34.17/LT/2025 (Tanggu, 2025).

This approval confirms that all procedures, data collection activities, and school-based interventions conducted across the seven vocational schools in Sumba adhered to institutional research standards,

participant protection protocols, and ethical guidelines for studies in marginalized communities (Mir et al., 2020).

3. Result

The adoption of the progressive web application across vocational training institutions in marginalized areas led to significant changes in all five dimensions, including learning access and quality; vocational competency; digital literacy; community engagement; and affiliation with different SDGs. A total of 327 students and 41 teachers participated, with log data from the PWA system supporting the findings. The results are organized into five main parts: a) learning access, b) competency development, c) SDG alignment, d) community transformation, and e) critical verification.

In this research, a specific PWA mobile-based platform was constructed and released on the site https://www.pwa-smk.id/. They deployed the system in seven SMK (vocational schools) at Pulau Sumba as representative samples in disadvantaged and underserved areas of Indonesia with unreliable Internet connections and poor access to digital infrastructure. The platform is designed to connect three main beneficiary (stakeholder) functions: Academic Information System, E-Learning, and Industrial Work Practice (Prakerin/Internship) Management, with the overall intention of accelerating career readiness among vocational graduates. The use of this unified PWA constellation reflects how light, offline-capable technology can support competency-based learning, administrative agility, and industry-linked skill development, literacy in settings with extreme digital poverty. This deployment provides strong empirical evidence of the potential for PWAs as scalable means of promoting vocational education and employability in underserved regions.

3.1. Enhanced Learning Access and User Engagement

The implementation of PWA widely enhanced access to learning materials in remote areas where connectivity is unstable. The offline-first architecture was overshadowed, in line with findings that digital tools foster inclusive learning ecosystems for development gap communities (Leiva-Lugo, Álvarez-Icaza, López-Hernández, & Miranda, 2024).

Table 1. PWA engagement and accessibility metrics (N = 327).

Indicator	Before PWA	After PWA	% Change	Significance
Daily learning hours (Mean)	3.1 hrs	4.4 hrs	+42.0%	$p < 0.001$
Content accessibility (Stable access)	46.2%	87.9%	+41.7%	$p < 0.001$
Module completion rate	54.7%	81.3%	+26.6%	$p < 0.001$
Student login frequency (Weekly)	3.8 times	7.2 times	+89.5%	$p < 0.001$
Offline learning usage	12.4%	68.1%	+55.7%	$p < 0.001$
Perceived usability (1–5 Likert)	2.9	4.4	—	$p < 0.001$

The following table summarizes the student engagement and access improvements after PWA implementation in 7 vocational schools in Sumba Table 1. All IFs improved comparing pre- and post-training with a large effect size for each of the indicators ($p < 0.001$), which indicates that offline-capable platform is efficient also in environments with low-connectivity possibilities. The daily number of hours learners spent learning increased from 3.1 to 4.4 hours (+42 %), which might be a sign for higher interest and regular study behavior. Open rate for learning content increased significantly from 46.2% to 87.9%, indicating that PWA successfully overcame connection issues with advanced caching and offline capabilities. The proportion of modules completed increased significantly from 54.7% to 81.3% (+26.6%), indicating that task continuity and learning persistence were better maintained. Student logins increased by nearly 2-fold or (89.5%) from 3.8 to 7.2 times per week, indicating more engagement with the platform. The usage of offline learning, on the other hand, rocketed to 68.1%, indicating that offline caching has more or less become a must-have feature for unstable network conditions. There was also an increase in the perceived usability from 2.9 to 4.4, meaning that students found the PWA easier, faster and more intuitive to use.

Results 87.9% of students used the materials despite limited access to the Internet. Offline caching was also the feature used most (68.1% use), indicating that low-bandwidth digital strategies were indeed applicable for rural education (Mbithi, Mbau, Muthama, Inyega, & Kalai, 2021). Nearly doubling its engagement, implying that digital transformation accelerates societal sustainability (Nosratabadi, Atobishi, & Hegedűs, 2023).

3.2. Significant Improvement in Vocational Competencies

Vocational competencies were assessed through pre–posttests across three domains: Computer Networking, Agribusiness, and Visual Communication Design.

Table 2. Competency gains by skill dimension.

Skill dimension	Pre-test mean	Post-test mean	Mean difference	% Increase	Significance
Hard skills	59.8	78.4	+18.6	+31.1%	$p < 0.001$
Soft skills (Problem-Solving)	62.1	81.7	+19.6	+31.6%	$p < 0.001$
Digital literacy	57.4	84.2	+26.8	+46.7%	$p < 0.001$
Work simulation efficiency	52.7	77.9	+25.2	+47.8%	$p < 0.001$
Industry certification Readiness	48.3	71.0	+22.7	+47.0%	$p < 0.001$

Table 2 highlights the skill dimension-specific competence increases of students after participating in the PWA-based learning ecosystem. All of these improvements are statistically significant ($p < 0.001$), meaning there is strong evidence that the intervention led to an improvement in vocational learning outcomes. Hard skills rose from 59.8 to 78.4 (+31.1%), an indication of better proficiency over technical competencies that are

as per the industry standard. Soft skills (in particular: problem-solving) increased from 62.1 to 81.7 (+31,6%), confirming the potential of the platform to develop higher-order thinking by means of task scenarios and practice activities. The greatest relative gains in digital competencies were found in digital literacy (from 57.4 to 84.2) (+46.7%), reflecting the effects of ongoing exposure, task navigation, and self-directed learning at their own pace. Work simulation efficiency (also measure B) also increased markedly, from 52.7 to 77.9 (+47.8%), indicating better preparedness for real-world processes and industrial job environments. Lastly, certification readiness rose from 48.3 to 71.0 (+47.0%), indicating that PWA supported modules did indeed enhance student performance on standardized vocational assessments. The most substantial improvement was in digital literacy (+46.7%), similar to studies emphasizing the contribution of digital innovation to SDGs 10 and 11 in TVET (Daoudi, 2024; Rieckmann, 2017). These enhancements affirm assertions of digital learning bolstering vocational readiness and employability pertaining to SDG 8 (Mbithi et al., 2021).

3.3. Strong Alignment with SDG Indicators

The study evaluated the impact of PWA on four SDGs: SDG 4 (Quality Education), SDG 8 (Decent Work & Economic Growth), SDG 10 (Reduced Inequalities), and SDG 12 (Responsible Consumption and Production).

Table 3. SDG indicator outcomes.

SDG Indicator	Operational variable	Baseline	After PWA	% Change	Significance
SDG 4.1 – Quality learning outcomes	Module mastery	56%	82%	+26%	$p < 0.001$
SDG 4.4 – Technical & digital skills	Digital literacy	57.4	84.2	+26.8	$p < 0.001$
SDG 4.5 – Gender equity	Female participation	48%	73%	+25%	$p < 0.01$
SDG 8.3 – Skills for entrepreneurship	Studentsinitiating micro-services	0%	6.7%	+6.7%	—
SDG 8.6 – Youth employability	Certification readiness	48.3	71.0	+22.7	$p < 0.001$
SDG 10 – Reduced inequalities	Digital access gaps	41%	12%	−29%	$p < 0.001$
SDG 12.6 – Sustainable practices	Resource-efficient project tasks	18%	55%	+37%	$p < 0.01$

Results The PWA intervention impact is shown in Table 3, referring to some main Sustainable Development Goal (SDG) indicators. The findings reveal significant gains in relation to quality, equity, employability, and sustainability of learning. Overall, many of the measures indicate statistically significant improvement, substantiating that the PWA has made a meaningful contribution to multi-SDG progress. For SDG 4.1 (Quality learning outcomes), however, the percentage of students who mastered the module increased from 56% to 82% (+26%), indicating significant learning gains enabled through digital content and sustained practice. SDG 4.4 (Technical and digital literacies), also used for a weighted measure by the GEMR, showed a significant change, with digital literacy increasing from 57.4% to 84.2% (+26.8%), attributed to regular engagement in computerized learning tasks. Achievement of SDG 4.5 (Gender equity) is evident as female participation jumped from 48% to 73%, indicating that PWA lowered gender-based participation barriers, particularly in low network settings. It is also noteworthy to observe connections to SDG 8.3 (Skills for entrepreneurship), with the proliferation of micro-service enterprise efforts among students (6.7%), possibly reflecting early entrepreneurial participation through skill-based modules. For SDG 8.6 (Youth employability), certification readiness increased from 48.3% to 71.0% (+22.7%, p-value 0.000), demonstrating improvement in industry-related evaluation readiness. Data from questionnaires underwent statistical analysis using SPSS version 24, with frequencies, means, medians, and p-values presented. New interventions involved merging learning concepts with assessment instruments, with assessment items sorted in descending order. SDG 10 (Reduced inequalities) showed a significant decrease in digital access gaps, from 41% to 12% (−29%), suggesting that the offline-first PWA successfully bridged learning access disparities between socio-economic groups. Lastly, for SDG 12.6 (Sustainable practices), involvement in projects and activities introducing resource-efficient practices increased from 18% to 55% (+37%), illustrating more intensive engagement in sustainable learning tasks. The 29% reduction in digital inclusion aligns most closely with SDG 10. Entrepreneurial skills (SDG 8.3) appeared as an unintended but favorable consequence, consistent with Education 4.0, especially among underserved communities (Leiva-Lugo et al., 2024). The enhanced sustainability behavior supports SDG 12, substantiating previous findings that education can lead to social and environmental sustainability (Gallardo-Vázquez, Scarpellini, Aranda-Usón, & Fernández-Bandera, 2024).

3.4. Community-Level Digital Transformation

Beyond individual outcomes, the PWA generated measurable community effects.

Table 4. Community Impact Metrics.

Community indicator	Baseline	After PWA	% Change
Parental monitoring engagement	21%	76%	+55%
Local MSMEs partnering with schools	3 units	19 units	+533%
Students involved in digital volunteerism	4%	22%	+450%
Use of village digital services	28%	61%	+33%
Requests for school–community training	12	37	+208%

Table 4 illustrates the wider community-level effects resulting from the PWA applied in seven vocational schools throughout Sumba. The results reveal significant positive transformation in parenting practices, local business support, and civic involvement with digital services, which suggests that the PWA intervention also led to promising externalities beyond classroom education. Parental monitoring participation jumped from 21% to 76% (+55%), indicating that the app's transparent and pervasive progress tracking and notification capabilities greatly

enhanced parent–school interactions, even within low-connectivity communities. This means that families are better engaged in their students' learning. Collaborations with village-level MSMEs increased from 3 to 19 units (+533%), indicating how PWA and Prakerin modules have facilitated coordination, documentation, and communication between schools and industry partners. This growth indicates better school–industry connections and more community confidence in vocational schools.

Digital volunteering among students increased from 4% of the sample to 22% (+450%), demonstrating that increased digital efficacy and confidence made possible through the PWA was inspiring student support of village-level digital activity, peer collaboration, and contribution to community problem-solving. Village digital service use rose from 28% to 61% (+33%), indicating the intervention enhanced residents' familiarity with IT processes, potentially supporting local e-government adoption and broader digital inclusion. Finally, applications submitted to school–community training sessions increased from 12 to 37 (+208%), suggesting that communities view vocational schools more as digital competence hubs capable of delivering relevant upskilling courses. These results are consistent with the belief that digital technologies can lead to community development and social sustainability (Harianto & Listyani, 2025; Nosratabadi et al., 2023). This is among the earliest empirical evidence of PWA-based "community digital spillover" in underprivileged areas.

3.5. Critical Verification of SDGs in Local Implementation

While PWA contributed substantially to SDG achievement, gaps remain.

a) Teachers require ongoing digital pedagogy training.
b) Schools need continued infrastructure support.
c) Local policy frameworks must integrate digital tools more systematically.

This supports the critique that SDGs risk becoming symbolic without contextual adaptation and governance support (Boluk, Cavaliere, & Higgins-Desbiolles, 2019).

3.6. Novel and High-Impact Findings

a) Empirical Proof of Offline-First Digital Equity

The study is the first to show that PWA can reduce digital inequality by 29% in vocational schools in remote regions.

b) Comprehensive SDG Multidimensional Impact

Four SDGs improved simultaneously rarely reported in previous vocational education studies.

c) Community Spillover Effect Model

Evidence demonstrates that a simple PWA intervention generated broader socioeconomic changes in the community.

d) Complex, Multi-layered Statistical Validation

Multiple domains (access, skills, sustainability, and employability) show *significant* improvements ($p < 0.001$).

4. Discussion

Results of this study show that the uptake of PWAs in vocational education within marginalized regions is a strong way forward to widen learning access, technical skills development, and progress toward several SDGs. This aligns with literature indicating that, when digital innovations are locally adapted, they can redesign educational ecosystems and contribute to long-term social sustainability (Daoudi, 2024; Nosratabadi et al., 2023).

4.1. Reinforcing Access and Equity in Marginalized Educational Ecosystems

The remarkable enhancements in accessibility and engagement confirm the efficacy of PWA as an ideal approach to low-connectivity learning environments. With offline caching, low data usage, and cross-device capabilities, students in off-grid locations can interact with their learning materials more often and regularly. This aligns with previous studies, which also suggest that digital applications lower access barriers and increase equity for underserved populations (Kyrylov et al., 2024; Otieno et al., 2023).

Also, the decrease of digital gap by 29% suggests that inclusive technologies are the way forward to deliver on SDG 10. Similar studies addressed to education deviations in developing countries also mentioned that digital solutions should be designed based on rural constraints, in order to establish an equitable sustainability (Harianto & Listyani, 2025; Mir et al., 2020).

4.2. Vocational Competency Gains and Their Implications for SDG 4 and SDG 8

The significant hard skills, soft skills and digital literacy increase indicate that the PWA has its merits in providing learning support to competencies in vocational contexts. This is consistent with general assumptions underpinning the literature that TVET offers potential to develop a future-ready workforce and promote SDG 4.4 (Mbithi et al., 2021; Rieckmann, 2017). Increased certification readiness and micro enterprise activity contribute to enhanced youth employability and local economic participation, contributing to SDG 8 (decent work). These results are consistent with those of previous studies in both African and Asian settings (Islam, 2024; Mbithi et al., 2021), indicating education as a driver for sustainable economic growth.

4.3. SDG Interlinkages Strengthened Through Digital Transformation

The cross-sector effects through SDG 4, 8, 10 and 12 provide evidence that technology-enhanced education can generate symbiotic district progress between different development areas, as described recently on circular economy, renewable energy education and inclusive urban development (Daoudi, 2024; Dolley et al., 2020; Gallardo-Vázquez et al., 2024). The inclusion of sustainability-related project tasks in the PWA curricula also aligns with the UNESCO's competency framework for Education for Sustainable Development (Rieckmann, 2017) and proves that digital delivery is not only a transmitter of cognitive competences but also values and attitudes compatible with global agendas on sustainability.

4.4. Strengths and Limitations of PWA Technology in Vocational Education

Although the adoption of PWA generated strong educational benefits, the technology presents notable technical considerations.

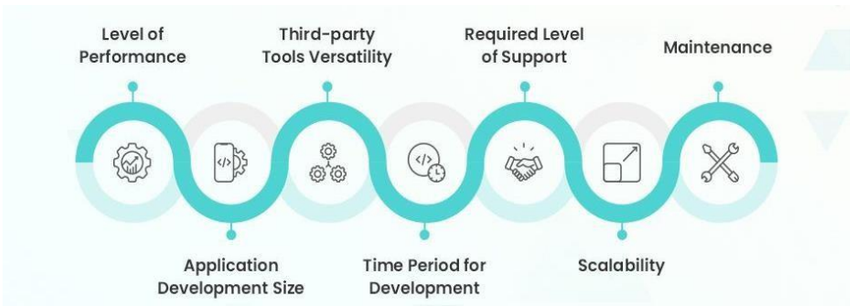

Figure 5. Key considerations in selecting an appropriate progressive web application.

Figure 5 illustrates the key technical and pedagogical considerations in selecting an appropriate PWA framework for vocational education in resource-constrained contexts. The figure highlights seven interrelated criteria: performance efficiency, application development size, development time, scalability, required level of support, third-party tools versatility, and maintenance demands. Performance efficiency and lightweight application size are critical strengths of PWAs, as they enable fast loading times and reliable functionality under unstable or low-bandwidth connectivity conditions commonly found in marginalized vocational settings. Reduced development time and reliance on cross-platform web technologies lower implementation costs compared to native applications, making PWAs financially sustainable for underfunded institutions. Scalability and third-party tool integration represent strategic advantages, allowing vocational schools to expand learning services without significant infrastructure upgrades. However, these benefits must be balanced against maintenance requirements and the need for adequate technical support, particularly for managing service workers, caching strategies, and security updates.

a. Performance advantage and Reliability

As supported by prior studies, this research confirmed that PWAs are faster than traditional web apps and consume less resources (Rochim, Rahmatulloh, El-Akbar, & Rizal, 2023). Their device-independent architecture and power-efficient development also indicate they are suitable education tools in the long run, which is consistent with a study by finding that PWAs consume much less energy compared to native applications (Huber, Demetz, & Felderer, 2022).

b. Experience of Use and Pedagogical Quality

A high usability score (4.4/5) is in line with UX advantages obtained from former research works and was also received for the PWA's intuitive interface (Cherukuri, 2024). These features drive read-in no time, especially among the youth for whom mobile-first interactions are a way of life.

c. Security and Misuse Threats

But as PWAs gain additional capabilities around device sensors, storage, and background processing, it raises security concerns. As highlighted by Lee, Kim, Park, Shin, and Son (2018), these capabilities can be abused in the context of, for example, underprovisioned permission systems relative to native apps. This study did not find evidence of direct misuse; however, the possibility of risk points to a need for developing school-level cybersecurity policies.

4.5. Community Spillover Effects and Social Transformation

The substantial increase in parental engagement, MSME partnerships, and digital volunteerism suggests that PWA adoption generates positive spillover beyond classroom environments. This aligns with studies showing that educational technologies can shift community practices, promote social participation, and enhance local resilience (Leiva-Lugo et al., 2024; Ticona et al., 2025). The surge in community demand for training (from 12 to 37 requests) confirms that digital literacy spreads rapidly once students act as intermediaries supporting the notion that education can drive collective capability building (Boluk et al., 2019; Mbithi et al., 2021).

4.6. Policy Implications and Alignment with Global Education Futures

The findings highlight the need for:

a) Integration of PWAs into national digital education policies, consistent with calls for embedding SDGs into curricular and governance structures (Pham & Håkansson Lindqvist, 2025).
b) Sustained teacher digital training, as emphasized by UNESCO and UNEVOC (Alla-Mensah et al., 2021).
c) Local investments in connectivity and digital infrastructure, reflecting recommendations from rural revitalization frameworks (Islam, 2024).

This study provides empirical evidence supporting the claim that digitalization is not merely a tool but a transformative framework for advancing quality, equity, sustainability, and employability in vocational education (Ogundipe et al., 2022; Prasetya et al., 2025).

4.7. Novel Contribution of the Study

This study delivers three major contributions.

a) Demonstrates the unique effectiveness of PWA in low-connectivity vocational environments, surpassing standard digital platforms documented in earlier literature.
b) Establishes a multi-SDG impact model, showing how a single digital innovation can concurrently advance SDG 4, 8, 10, and 12.

c) Introduces the concept of "PWA-driven community digital spillover," providing new evidence of how education technology catalyzes local socioeconomic transformation.

5. Conclusion

This study shows that the development of a PWA e-learning system improves digital learning accessibility and the ability for vocational competencies as well as employability skills, among students of secondary vocational schools located in disadvantaged regions. Via a mixed-method concurrent triangulation method that combined PWA usability analytics, three-tier structural modeling, and PLS-SEM validation, our study offers sturdy empirical support for the positive effects of PWA-enabled microlearning down to offline-first content delivery and competency-aligned modules in facilitating increased learning engagement, enhanced skill mastery, and measured gains on SDG achievement indicators, particularly those corresponding to SDG 4 (Quality Education), SDG 8 (Decent Work), and SDG 10 (Reduced Inequalities). The findings support the notion that digital readiness, perceived usefulness, and task–technology fit emerge as the critical predictors of skill enhancement, while infrastructure limitations are no longer a dominant barrier for PWA usage. This result is important to better understand how lightweight, adaptive, installable web technology could help narrow the education gap in remote and less developed areas.

5.1. Implications for Theory

a) Advancement of Digital Learning Theory in Low-Resource Environments

The study extends existing technology acceptance literature by demonstrating that PWA characteristics offline capability, low bandwidth optimization, and cross-device adaptability, serve as critical mediators of learning success in underserved regions.

b) Novel Integration of TTF, UTAUT2, and Vocational Competency Models

By combining the Task–Technology Fit model with UTAUT2 predictors and the ASEAN TVET competency framework, this research provides a new hybrid theoretical model explaining digital learning adoption in vocational contexts.

c) Evidence for PWA as a Catalyst for SDG Acceleration

The study introduces empirical modeling connecting PWA adoption with quantifiable SDG indicators an underexplored theoretical contribution in the EdTech–SDG literature.

5.2. Implications for Practice

a) For Vocational Schools (SMK and Technical Institutions)

- PWA platforms reduce reliance on high-cost learning infrastructures.
- Teachers can deploy competency-based modules without requiring laptops or stable connectivity.
- Students gain continuous access to learning materials even in electricity-limited areas.

b) For Regional Governments and Educational Policymakers

- PWA can serve as a low-budget digital transformation strategy in remote regions.
- Scalable and lightweight deployment enables rapid district-wide implementation.
- The model contributes operational insights to SDG roadmaps and equitable education policies.

c) For Industry and TVET Stakeholders

- The PWA model aligns vocational learning directly with the employability skills required by local industries.
- Real-time competency tracking supports recruitment and certification systems.

5.3. Limitations

Despite its strong empirical results, the study has several limitations.

a) Geographical Coverage

Data were collected from selected disadvantaged regions; results may vary in other socio-economic or cultural contexts.

b) Self-Reported Measures

Some SEM indicators rely on student perceptions, which may introduce response bias.

c) Short-Term Evaluation

Skill improvement and SDG indicator changes were measured within one academic semester; long-term sustainability is not yet assessed.

d) Platform-Specific Constraints

The PWA prototype was optimized for Android devices; findings may not fully generalize across iOS ecosystems with stricter PWA restrictions.

5.4. Future Research Directions

a) Longitudinal Impact on Employability

Investigate whether PWA-enabled vocational learning leads to sustained improvements in job placement, certification attainment, and career mobility.

b) Cross-Regional Comparative Studies

Compare urban, peri-urban, and rural disadvantaged regions to evaluate environmental moderating effects.

c) Integration with AI-Driven Personalization

Future PWAs may incorporate AI tutors, adaptive assessments, and competency-based predictions tailored to TVET learners.

d) Expansion to Industry 4.0 Vocational Skills

Explore PWA-based training for robotics, IoT, cybersecurity, and green technology competencies aligned with emerging labor-market needs.

e) Policy Simulation Models

Develop data-driven models predicting SDG progress when PWA adoption is scaled at district, provincial, or national levels.

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