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Developing a Mobile Application for Community Forest Sequestration Assessment: A Mixed-Methods Study

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Abstract

A mobile application for community forest carbon sequestration assessment serves as a critical tool for supporting family forest management amidst climate change. This study aimed to design and evaluate the usability of a specialized carbon calculation application tailored for farmers using a mixed-methods approach. A sample of 29 farmers assessed the application via the System Usability Scale (SUS) and in-depth interviews. Results yielded a good average usability score (M = 76.90, SD = 14.12), with no statistically significant difference between trained and untrained users ($t(27)$ = 0.326, p = 0.746; Mann-Whitney U = 113.0, p = 0.709), and a negligible effect size (Cohen's d = 0.123). Qualitative insights corroborated these quantitative findings, highlighting high user satisfaction regarding ease of use (82.8%) and interface simplicity (65.5%). While users suggested expanding plant species databases and refining data input systems, the findings overall demonstrate that the application's intuitive design facilitates practical usability without necessitating prior training. Enhancements to system stability are recommended to further optimize the user experience.

Keywords: Forest Carbon; Carbon Sequestration Assessment; Mobile Application; System Usability Scale.

1. Introduction

Climate change has contributed to the intensification of El Niño and La Niña phenomena, both of which have had significant global impacts, including on Thailand [1, 2]. Collectively referred to as the El Niño–Southern Oscillation (ENSO), these climatic events are characterized by contrasting oceanic and atmospheric conditions in the Pacific Ocean. El Niño is associated with warmer sea surface temperatures in the eastern Pacific and weakened trade winds, while La Niña involves stronger trade winds and cooler sea surface temperatures. Both phenomena have direct implications for Thailand's climate, affecting sectors such as agriculture, water resource management [3, 4], urbanization, and the increasing frequency of extreme weather events [5-8].

In response to these climate-related challenges, Thailand's 13th National Economic and Social Development Plan outlines key priorities, including the promotion of a circular economy, the transition to a low-carbon society, and the reduction of risks associated with natural disasters and climate change. The country has committed to achieving carbon

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neutrality by 2050 and reducing greenhouse gas emissions by 40% by 2030. As part of this commitment, enhancing greenhouse gas reduction, absorption, and sequestration within the forestry and agricultural sectors has become a national priority [9]. The capacity of trees to sequester carbon is critical for achieving several Sustainable Development Goals (SDGs), particularly SDG 13 (Climate Action) and SDG 15 (Life on Land). Therefore, the implementation of measures that promote carbon sequestration plays a vital role in advancing Thailand's sustainable development agenda [10].

Within this context, family forests are gaining renewed attention; these forested areas are privately managed and overseen by individual households for both economic and subsistence purposes [11]. Unlike community forests, which are typically co-managed with the state, family economic forests focus on long-term cultivation of trees on private land, with the aim of generating income from both non-timber forest products and future timber yields [12-15]. Economically valuable tree species in Thailand, such as Yangna (Dipterocarpus alatus), Pradoo (Pterocarpus macrocarpus), Payom (Shorea roxburghii), teak (Tectona grandis), and agarwood (Aquilaria spp.), along with commonly found species such as Takian (Hopea odorata), bamboo, eucalyptus, and Leucaena leucocephala, are eligible for participation in carbon sequestration programs and carbon credit markets. The Forestry and Agriculture Greenhouse Gas Reduction, Removal, and Sequestration Project [16] enables such participation by relying on key biometric parameters, specifically, diameter at breast height (DBH) and tree height, which are essential for calculating tree volume and biomass.

While these biometric parameters are essential for carbon estimation, traditional field-based methods for measuring them, such as using calipers for diameter and clinometers or hypsometers for height, present several limitations. These include high operational costs, time-intensive procedures, lack of real-time data integration, difficulties accessing remote or rugged terrain, and potential for measurement errors [17, 18]. Furthermore, for many farmers, performing these calculations independently remains a significant challenge [19].

In light of these limitations, the use of mobile applications for tree measurement and carbon sequestration assessment has gained considerable interest. These digital tools harness advanced sensors and algorithms to measure biometric variables, such as DBH, tree height, and crown diameter, with improved speed, accuracy, and automation [20, 21]. Additionally, they allow for real-time data collection and automated calculations of volume and biomass [22, 23]. These technological innovations empower farmers and local communities to manage community and family forests more effectively. For example, they can be used to assess the carbon credit potential of forest areas, thereby generating supplementary income, promoting awareness of the ecological and economic value of trees and forests, and informing land-use planning. Ultimately, these applications can support tree planting initiatives aimed at increasing carbon sequestration [24-26].

Given this potential, evaluating the usability and functionality of mobile applications designed for carbon sequestration estimation is essential not only to encourage adoption in field workflows but also to ensure that interface friction does not compromise measurement efficiency, data quality, or user confidence. Across recent applied domains, especially mHealth and other high-stakes mobile tools, usability evaluation has increasingly moved beyond "satisfaction only" toward evidence-based assessment that links perceived usability to observable task performance and implementation feasibility. Large-scale benchmarking work confirms that the System Usability Scale (SUS) remains a practical, comparable indicator of perceived usability across app categories, while also showing that SUS scores are more actionable when interpreted alongside workflow context and user characteristics [27-30]. Complementary methodological advances further emphasize task analysis, objective performance indicators, such as time on task and error rates, and richer interaction evidence to reveal where and why breakdowns occur [31]. In parallel, mixed-methods evaluations continue to demonstrate that combining standardized scales with qualitative inquiry strengthens design implications and improves the explanatory power of findings, particularly for complex, real-world mobile work [32].

Primarily, a mixed methods approach anchored in the System Usability Scale provides a robust basis for evaluating usability and user experience by combining quantitative indicators such as SUS scores, task completion rates, error frequency, and efficiency measures with qualitative evidence from interviews, think-aloud protocols, and open-ended feedback. Qualitative insights contextualize these quantitative outcomes by clarifying user mental models, surfacing terminology mismatches, and identifying workflow misalignments often invisible in summary scores, thereby enabling precise, user-centered redesign priorities [27, 33, 34]. Despite these methodological advantages, a notable gap remains in carbon-sequestration and forestry-oriented mobile application literature: many recent studies prioritize technical validity and measurement accuracy, such as smartphone and LiDAR enabled tree metrics, while reporting limited standardized evidence on end-user usability, learnability, and experience in operational settings [35-37]. Prior work on mobile technologies in forest mensuration highlights rapid capability growth and, consequently, underscores the need for more standardized, implementation-focused evaluation beyond accuracy alone [38]. To address this, the application was evaluated using a convergent mixed-methods framework synthesizing the System Usability Scale (SUS), objective task performance metrics, and qualitative inquiry. This approach enables both standardized usability quantification and a contextual interpretation of user experience, facilitating the diagnosis of field-relevant interface improvements for carbon sequestration estimation workflows.

2. Material and Methods

The development of an application for managing and evaluating carbon sequestration in family forest areas aims to enable tree owners to manage tree data, calculate, and independently verify carbon sequestration values. The project framework comprises four main phases: Planning, Conceptual Design, Development, and Testing. A prototype application was developed and tested through simulated tree measurement scenarios and user interaction. Usability testing was subsequently conducted using the System Usability Scale (SUS), followed by the collection of qualitative data through open-ended questionnaires. Data were then analyzed using a mixed methods approach, incorporating both quantitative analysis (Independent t-test, Mann-Whitney U test, and Spearman's correlation between age and SUS score) and qualitative analysis. The entire process followed the principles of Human-Centered Design (ISO 9241-210), emphasizing the active participation of farmers from the initial stages, as illustrated in Figure 1.

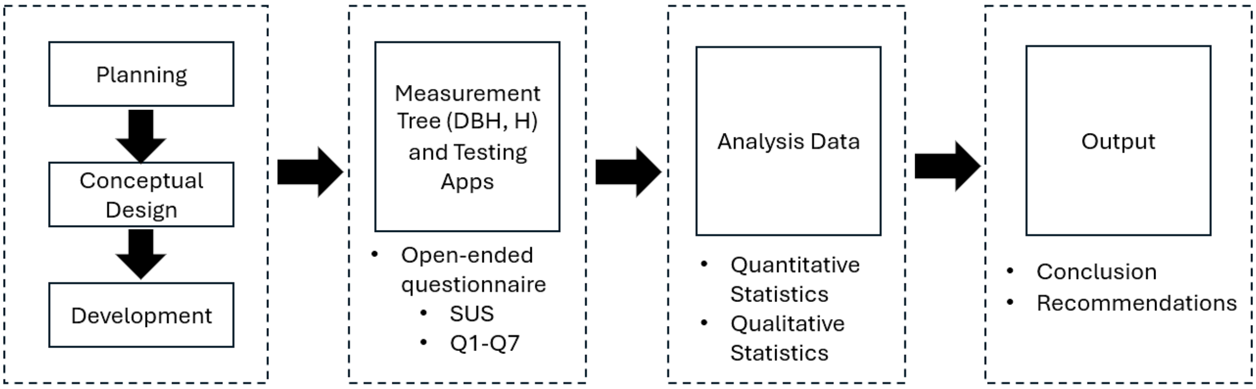

Figure 1. Operational framework for the Development of a Mobile Application for Managing and Evaluating Carbon Sequestration in Family Forests

The study is grounded in a human-centred, usability-oriented evaluation framework, drawing on established definitions of usability as the extent to which specified users can achieve specified goals with effectiveness, efficiency, and satisfaction within a defined context of use. Operationally, we adopt a convergent mixed methods design. In this design, the System Usability Scale provides a standardized measure of perceived usability. Task based performance metrics, such as task completion, time on task, and error patterns, capture effectiveness and efficiency. Qualitative inquiry, including think aloud protocols and semi structured interviews, explains the mechanisms behind the observed usability outcomes by revealing users' mental models, workflow fit, and points of interface breakdown. These components are synthesized to strengthen interpretability and to translate findings into prioritized, user-centered design recommendations for field-ready carbon sequestration estimation workflows.

After designing the tree database to store survey data, the researchers proceeded to develop the user interface and application functions, which were organized into four main tasks: initiating and recording tree owner information; editing tree owner information; recording and editing data on general tree species and palm species; and calculating and verifying the user's own carbon sequestration results. The user interface and corresponding functions were designed accordingly, as illustrated in Figure 2.

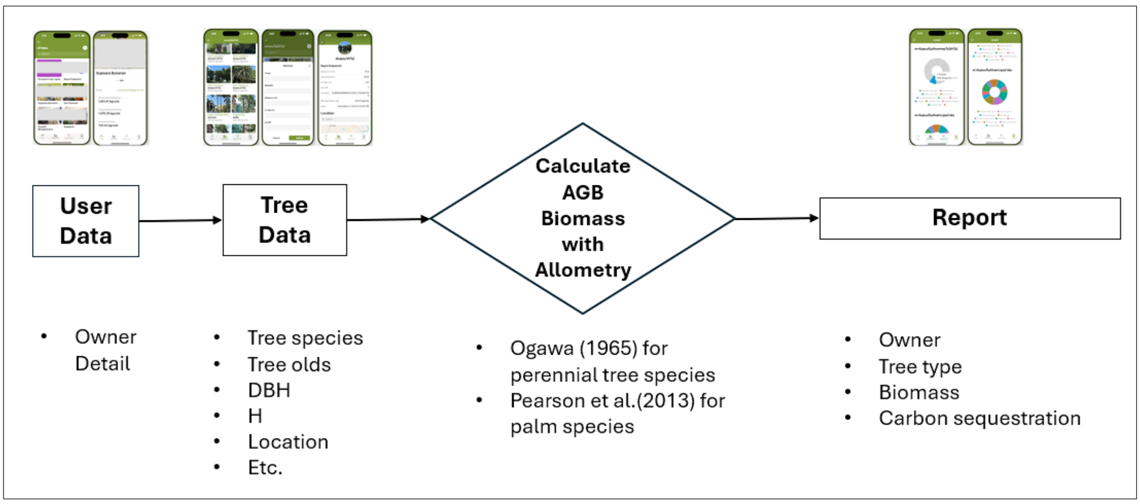

Figure 2. Operation of the Mobile Application for Managing and Evaluating Carbon Sequestration in Family Forests

The User section includes personal information and the individual's carbon sequestration results. The General Tree Species contains detailed tree data and a user interface for field data recording, which captures essential information such as the owner's name, species name, circumference, height, tree age, photograph, GPS coordinates via location services, and the date and time of data collection, as shown in Figure 3. The Palm Tree Species, including species such as palm, betel nut, and coconut, follows a similar data structure. The interface allows users to collect and record data in the field, including the same required fields as for general tree species. Upon completing the data entry, the system stores the information in the database and automatically calculates the carbon sequestration for each recorded palm species. Finally, the User Interface, which is the summary interface, presents the overall results, categorized into two groups: general tree species and palm species.

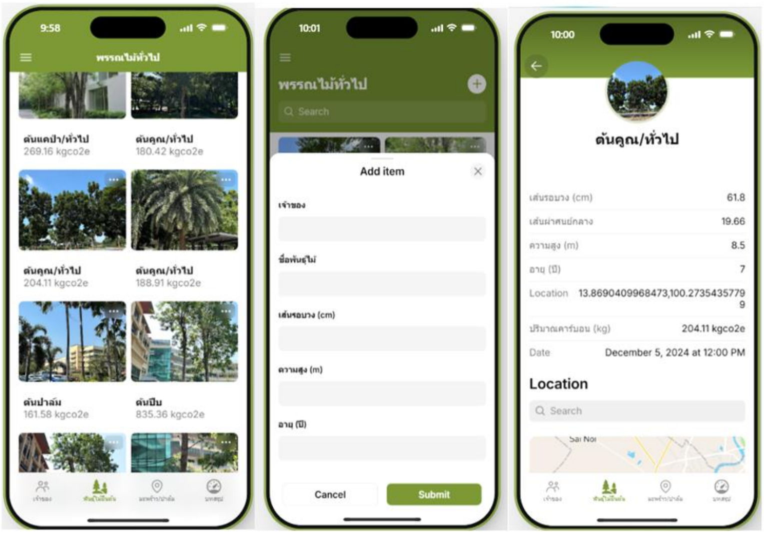

Figure 3. User Interface and Functions for General Tree Species

For the assessment of carbon sequestration in family forest areas, parameters such as diameter at breast height (DBH) and tree height were used to calculate tree volume and biomass [39]. The allometric equation developed by Ogawa et al. [40] was applied for woody tree species, while the equations proposed by Eggleston et al. [41] and TGO [42] were used for palm species.

2.1. Usability Testing Using the System Usability Scale (SUS)

The System Usability Scale (SUS) consists of 10 items rated on a 5-point Likert scale (1–5). It is a post-test questionnaire used to assess overall usability and user satisfaction following application testing. A rating of 1 represents "Strongly Disagree," while 5 represents "Strongly Agree." The items alternate between positive and negative phrasing, as shown in Table 1 [28, 43, 44].

For scoring, the positive items (Items 1, 3, 5, 7, and 9) are scored by subtracting 1 from the user's response. For the negative items (Items 2, 4, 6, 8, and 10), the response is subtracted from 5. The adjusted scores are then summed and multiplied by 2.5 to convert the total score into a scale from 0 to 100. SUS score interpretation is as follows: 0–50 = Poor, 51–68 = Fair, 69–80 = Good, and 81–100 = Excellent.

Table 1. SUS Items for Assessing Overall Usability and User Satisfaction

Item No.	Statement
1	I would like to use this application frequently when assessing carbon sequestration.
2	I find the application unnecessarily complex.
3	I think the application was easy to use.
4	I need technical support to be able to use this application.
5	I think the functions in this application work well.
6	I think the application did not function properly.
7	I could quickly learn how to use this application.
8	I think the application is too complicated or confusing to use.
9	I think the application meets my needs.
10	I needed to learn a lot of things before I could effectively use this system.

2.2. Qualitative Data Collection

Qualitative data were collected through a simulated tree growth measurement activity, during which participants used the mobile application to calculate tree volume and biomass. Following the simulation, participants completed the System Usability Scale (SUS) and subsequently responded to an open-ended questionnaire comprising seven core questions:

Q1. After using the application, would you consider using it again in the future to assess carbon sequestration? What is your primary reason?

Q2. What aspects of the application did you like or find satisfying, and why?

Q3. What aspects did you find least satisfactory or problematic during use?

Q4. Do you have any additional comments regarding your experience using the application?

Q5. Which features of the application did you find well-designed or particularly helpful, and why?

Q6. Which features did you find poorly designed or difficult to use, and why?

Q7. Do you have any further suggestions or comments regarding the application's functionality?

These questions were intended to assess user experience, including satisfaction, likelihood of future use, challenges encountered, key strengths, and suggestions for improvement. The sample consisted of 29 farmer participants aged 19–54 years (15 males, 14 females). Participants were selected through purposive sampling based on their prior use of the application and their relevance to the target deployment context. The sample size of 29 was considered methodologically appropriate for usability evaluation for two reasons. First, usability studies commonly employ small to moderate samples because a substantial proportion of usability issues can be identified with relatively few users, while larger samples, typically approximately twenty to thirty participants, provide more stable estimates for standardized usability metrics such as the System Usability Scale and support exploratory subgroup comparisons, for example between participants who received training and those who did not [45-47]. Second, for the qualitative component, data collection was continued until thematic saturation was observed in open-ended responses i.e., comments and usability issues became repetitive and no substantively new themes emerged supporting the adequacy of the sample for capturing user experience and improvement suggestions [48, 49].Training was implemented as a brief, standardized, in-person walkthrough with guided hands-on practice to ensure consistent exposure to the application workflow. Participants in the trained group received a page-by-page explanation of the main interface modules and then completed four predefined tasks: (1) launching the application and creating an owner (User) profile, (2) editing and updating owner information, (3) entering and editing field-survey records for both general tree species and palm-family species (including owner ID, species, circumference/DBH, height, tree age, photographs, GPS coordinates with Location Services enabled, and date/time of entry), and (4) calculating and verifying the carbon sequestration results generated from the stored records. The training also clarified how the system applies species groupings and allometric equations and provided concise guidance on field measurement procedures (DBH using a tape and height using a handheld laser rangefinder). This standardized format was used for all trained participants to support interpretation of between-group usability comparisons.

3. Results

Results from the user questionnaire regarding task completion time indicate that users recorded the duration required to complete each task. These included the time spent entering tree owner information, editing existing owner data, and recording or updating data for a single tree species. Additionally, users were able to interpret the carbon sequestration results in the summary section and verify their own carbon storage values. According to Table 2, the task involving the recording or editing of data for a single tree species (Task 3) was completed the fastest, with an average time of 1.97 minutes, followed by Task 2 (2.07 minutes), Task 4 (2.24 minutes), and Task 1 (2.31 minutes).

Table 2. The Completion Time for Each Task (in Minutes)

Task	Min	Max	Mean	S.D.
1	1	4	2.31	1.11
2	1	4	2.07	1.07
3	1	4	1.97	1.12
4	1	4	2.24	1.12

Table 3 presents SUS (System Usability Scale) results indicate that the application achieved good overall perceived usability in both the trained and untrained groups. The trained participants (n = 13) reported a mean SUS score of 77.88 (SD = 14.96), while the untrained participants (n = 16) reported a mean of 76.09 (SD = 14.32). Using the widely adopted

SUS reference point of 68 as an average benchmark, both group means are clearly above average, suggesting that users generally perceived the system as usable and acceptable. The between-group difference in means is small (approximate to 1.79 points) relative to the within-group dispersion (SD ≈ 14–15), implying substantial overlap in usability perceptions between trained and untrained users. In practical terms, these descriptive statistics suggest that the system's perceived usability is not strongly dependent on training, at least when considering overall SUS as a single summary measure.

Distributional summaries, however, reveal meaningful nuances that are not captured by the means alone. Scores span a wide range in both groups (Trained: 55.0–97.5; Untrained: 50.0–97.5), indicating heterogeneity in user experience: some participants perceived only moderate usability, whereas others rated the system near the ceiling. The medians show a slightly higher central tendency for the untrained group (Median = 78.75) than for the trained group (Median = 75.00), but the upper quartile tells a different story. The trained group's 75th percentile is notably higher (92.5) than that of the untrained group (85.0), suggesting that training may be associated with a more pronounced high usability subgroup, i.e., a portion of trained users reported very strong usability perceptions. Consistent with this, the interquartile range is somewhat larger for trained users (IQR = 25.0) than for untrained users (IQR approximate to 20.63), implying slightly greater variability among trained participants, potentially reflecting uneven benefits from training (some users gain substantial fluency, while others continue to encounter interface or workflow frictions). Taken together, these patterns support the conclusion that while overall usability is good across both groups, a subset of users visible in the lower tail (minimum scores around 50–55) still experiences difficulties that warrant targeted design refinement.

Table 3. SUS Statistics Categorized by Training Groups

Training	Amount	Mean	Std	Min	25%	50%	75%	Max
Trained	13	77.884615	14.959882	55.0	67.500	75.00	92.5	97.5
Untrained	16	76.093750	14.316912	50.0	64.375	78.75	85.0	97.5

Figure 4 presents the items of the System Usability Scale (SUS) suggests a consistently positive usability profile for the carbon sequestration assessment application. The positively worded items (Items 1, 3, 5, 7, and 9) achieved relatively high mean ratings, indicating strong perceived usefulness and ease of use: participants expressed willingness to use the application frequently (Item 1: score = 3.83), perceived the application as easy to use (Item 3: score = 3.90), judged its functions to work well (Item 5: score = 3.97), and reported that they could learn to use it quickly (Item 7: score = 4.10). Notably, the highest endorsement was observed for the application meeting users' needs (Item 9: score = 4.14), implying good alignment between system capabilities and task requirements in the target context. In contrast, the negatively worded items (Items 2, 4, 6, 8, and 10) received low mean ratings unnecessary complexity (Item 2: score = 1.93), need for technical support (Item 4: score = 1.90), malfunctioning perceptions (Item 6: score = 1.66), confusion or over-complication (Item 8: score = 1.83), and the need to learn many things before effective use (Item 10: score = 1.86) indicating that users generally did not experience the system as complex, unreliable, or difficult to learn. Taken together, this response pattern demonstrates strong perceived usability across both core SUS dimensions: users reported high learnability (rapid onboarding and low perceived learning burden) and high overall usability and acceptability (need fulfillment, functional adequacy, and willingness for continued use), supporting the conclusion that the application is well positioned for practical, field-oriented deployment.

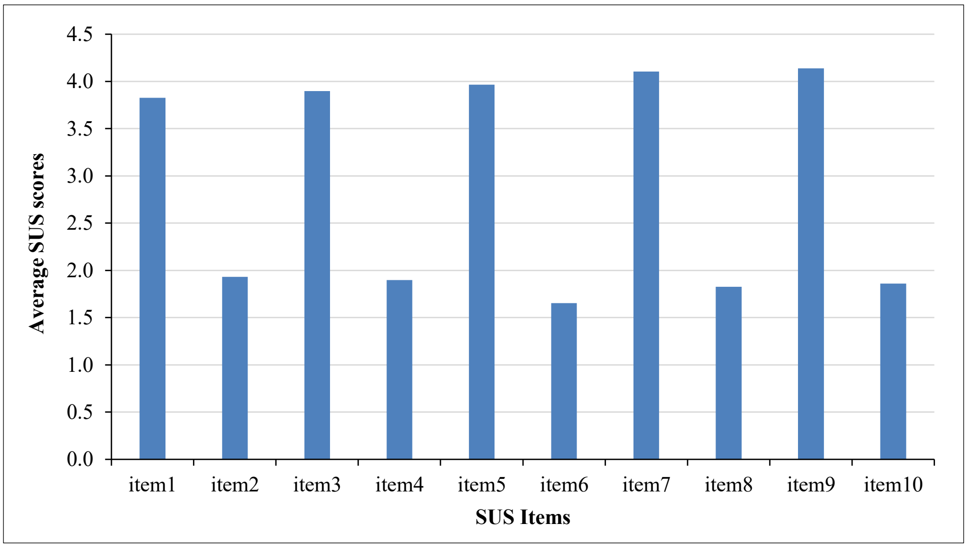

Figure 4. Average SUS Scores

Figure 5 shows the distribution of System Usability Scale (SUS) scores. Individual SUS scores ranged from 50.0 to 95.0, with an overall mean score of 76.90 and a standard deviation of 14.12. This indicates a moderate to high level of user satisfaction with the application [30, 43, 50, 51]. The sample of 29 participants was divided into two groups: 13 who received training and 16 who did not. Preliminary assumption testing was conducted. Levene's Test for equality of variances yielded $w = 0.026$, $p = 0.873$. The Shapiro-Wilk Test for normality indicated that both groups had normally distributed data: the "Trained" group showed $w = 0.912$, $p = 0.196$, and the "Untrained" group showed $w = 0.948$, $p = 0.453$. These results support the assumption of equal variances and normal distribution in both groups.

Figure 5. SUS Score Distribution

According to Table 4, the results of both the Independent t-test and the Mann–Whitney U test are consistent, indicating no statistically significant difference in SUS scores between the trained and untrained groups. The effect sizes from both tests ($Cohen's\ d = 0.123, r = 0.073$) suggest that training had no impact on SUS scores. Similarly, the Spearman's rank correlation analysis revealed no significant relationship between age and SUS score, indicating that age is not a factor influencing the usability of the application. These findings suggest that the application is intuitively designed and accessible for farmers across different age groups and levels of experience.

Table 4. Results of Parametric and Non-parametric Statistical Analyses

Variable/Test	Test Statistic	p-value	Effect Size	Interpretation
Independent t-test	t = 0.326	0.746	Cohen's d = 0.123	No statistically significant difference
Mann-Whitney U	U = 113.0	0.709	r = 0.073	No statistically significant difference
Spearman's R (Age vs SUS)	r = -0.041199	0.831	-	No statistically significant correlation

Table 5. Summary of User Satisfaction and Experience Analysis (n = 29)

Category	Key Themes	No. of Respondents (n)	Percentage (%)	Examples of Responses
Good	Easy to use/convenient	24	82.8	"Easy to use, not complicated"; "Fast calculation"
	Simple interface	19	65.5	"The app layout is easy to understand."
	Automatic calculation	18	62.1	"Immediate results"
Problems and Limitations	System instability	13	44.8	"The app crashes frequently."
	Data entry problem	11	37.9	"I have to re-enter data."
	Incomplete plant database	8	27.6	"More plant species should be added."
Recommendations	Improve system stability	15	51.7	"The crashes should be fixed."
	Add more plant types	8	27.6	"Add air-purifying plants."
	Improve data entry system	7	24.1	"The system should auto-fill names."

Note: Data were collected from 29 respondents (n = 29). Percentages reflect the proportion of respondents who mentioned each issue (n/29). Inter-coder reliability was verified using Cohen's Kappa (κ = 0.82), indicating a very high level of agreement.

Table 5 illustrates the results of the qualitative analysis, indicating a high level of user satisfaction with the application, particularly in terms of ease of use (82.8%) and the simplicity of the user interface (65.5%). These findings align with the SUS score, which falls within the "Good" range. However, system stability emerged as a key issue, with nearly half of the users (44.8%) reporting that the application froze or crashed during use. A notable strength of the application is its automatic carbon calculation feature, which was positively recognized by 62.1% of users. In contrast, key areas identified for improvement include the data entry process (37.9%) and the limited diversity of the plant database (27.6%), reflecting the users' need for more flexible and comprehensive functionality. These findings are summarized in Table 5.

As shown in Table 6, user satisfaction was primarily associated with the application's ease of use (reported by 22 participants) and system speed (18 participants), which were identified as the application's core strengths. In contrast, the most commonly reported usability issues included system instability (12 participants) and user interface (UI) design problems (9 participants), both of which significantly affected the overall user experience. Notably, 10 participants suggested that the application should include additional features, particularly a search function, and a wider variety of plant species for carbon estimation, highlighting key areas for future development.

Table 6. Thematic Analysis of Open-Ended Responses

Question	Identified Theme	Frequency (n)	Examples of Responses
Q2 (Positive aspects)	Ease of use	22	"It's easy to use without needing prior instruction."
	Speed	18	"The carbon calculation is very fast."
Q3 (Usability issues)	System crashes/unexpected shutdowns	12	"The data failed to save properly."
	Unstable UI	9	"Swiping the screen caused the app to crash."
Q7 (Recommendations)	Feature enhancement	10	"I'd like to see a search function added."

4. Discussion

In summary, qualitative analysis of user experiences with the carbon assessment application revealed four key themes: Ease of Use, Stability, Data Management Issues, and Recommendations for Improvement. The first theme, "ease of use," was consistently highlighted as a major strength. All users indicated that they no prior instruction, yet were able to operate it comfortably and intuitively. This was attributed to the application's simple interface and streamlined data entry functions. One participant commented, "It's easy to use and not complicated suitable for beginners," while another noted, "It's convenient and fast for calculating carbon." This aspect of usability strongly influenced users' willingness to continue using the application, underscoring the importance of intuitive design in facilitating adoption and field use.

However, system "stability" emerged as the most salient limitation reported by users. Several participants described intermittent disruptions during data entry, including occasional crashes or automatic shutdowns, and, in some cases, the need to re-enter information after an unexpected interruption. For example, one respondent noted, "While recording data, the screen often swipes away, so I have to re-enter everything," and another stated, "The app is still not stable enough." Notably, these events were observed primarily under prototype-stage field conditions and are most plausibly associated with resource-intensive operations, such as image capture and processing, repeated GPS and location requests with permission or state handling, and variable network connectivity during database synchronization, rather than with fundamental deficiencies in the application's core workflow logic. Future research should therefore strengthen reliability by implementing crash logging to identify reproducible failure points, optimizing image handling and location state and permission checks to reduce processing overhead, and adopting an offline-first saving mechanism with deferred synchronization when connectivity becomes available. Together, these steps are expected to improve stability and reduce the risk of data loss during entry; their impact will be verified through regression testing and reported in subsequent work. The third theme involved "data management challenges," particularly regarding the completeness and flexibility of the plant database. Several participants highlighted the inconvenience of redundant data entry and the absence of certain tree species within the current system. These limitations not only increase user burden and slow field workflows but also undermine perceived functionality and suitability for real-world deployment, especially in settings characterized by high species diversity.

The final theme concerned "recommendations" for improvement. Users provided targeted suggestions, beginning with the need to enhance system stability. This was followed by requests for a search function to help locate previously recorded tree data, which would support more efficient long-term data management. For instance, one participant noted, "There should be a search tool for recorded tree data in the app." Collectively, these user-driven insights provide a practical roadmap for developers to refine the application in alignment with real operational needs and field workflows. Nevertheless, these recommendations should be interpreted in light of key study limitations. First, participants were recruited based on prior use of the application, which may have introduced positive bias in perceived usability and satisfaction ratings. Familiarity with the interface can reduce perceived complexity, increase confidence, and shape the nature of feedback (e.g., emphasizing feature enhancements rather than initial onboarding difficulties). As a result, the reported themes may reflect the perspectives of users who had already developed baseline proficiency, potentially underrepresenting barriers faced by first-time users. Second, task performance timing was recorded manually using a stopwatch by an observer; although this approach reduces self-report bias, it may still introduce minor measurement error (e.g., start/stop reaction time, ambiguity in defining the exact completion moment for multi-step screens, and field-context variability such as GPS acquisition delays or intermittent connectivity). Accordingly, task time should be interpreted as an approximate performance indicator rather than a precise system-level latency measure. Future evaluations should therefore include novice participants and explicitly compare first-time versus experienced users to capture learnability, onboarding friction, and early-stage error patterns more comprehensively, while also adopting system-logged timestamps/usage logs to improve timing precision, thereby strengthening the generalizability of both usability findings and user-driven recommendations for wider deployment.

When benchmarked against prior literature, the present study indicates that the application achieved good perceived usability, with overall SUS performance exceeding the commonly used practical reference point of approximately 68, which is frequently interpreted as "average" usability. This pattern is consistent with large-scale evidence showing that SUS provides a stable, standardized metric for cross-study comparability in mobile applications and that scores above this benchmark typically reflect a level of user acceptance compatible with real-world implementation [28, 52]. In addition, the item-level response profile observed here strong endorsement of positive statements related to ease of use, rapid learnability, and needs fulfilment, alongside low endorsement of negative statements concerning unnecessary complexity, reliance on technical support, and malfunctioning aligns with mixed methods usability research emphasizing that questionnaire-based outcomes become more interpretable and actionable when situated within task demands and user context [31, 32]. Importantly, this contribution is particularly salient in the broader domain of forestry- and carbon-related field technologies, where many studies have historically prioritized technical or measurement validity while offering comparatively limited standardized, user-centered usability evidence. By foregrounding usability through SUS and interpreting the results through an implementation-oriented lens, the present study extends the evaluation focus beyond accuracy alone and strengthens the case for field readiness, while also providing clearer direction for interface and workflow refinements that support practical deployment in carbon sequestration assessment settings [36, 38].

5. Conclusion

Carbon sequestration assessment in smallholder and community forestry is inherently complex because it requires farmers to collect biometric parameters (e.g., diameter at breast height: DBH, and total height: H) and apply species-specific allometric equations to derive biomass and carbon estimates. To reduce these practical barriers, this study developed a prototype mobile application supported by a spatial database to assist farmers and communities in forest management and carbon sequestration assessment in family forest areas. The application was evaluated using a mixed methods framework combining the System Usability Scale (SUS) with open-ended feedback, enabling both standardized usability quantification and contextual interpretation of user experience. Overall findings indicate that user satisfaction and perceived usability fall within the "Good" range. The item-level response pattern further supports this conclusion participants strongly endorsed statements related to ease of use, rapid learnability, functional adequacy, and needs fulfilment, while reporting low perceptions of unnecessary complexity, reliance on technical support, and malfunctioning. Importantly, trained and untrained users reported comparable usability perceptions, suggesting that the application workflow is sufficiently intuitive to support independent use without extensive prior instruction and may therefore be suitable for field-oriented deployment.

Despite these promising results, qualitative feedback identified areas requiring refinement prior to broader implementation, particularly regarding system stability, interface clarity, and workflow robustness under real field conditions. Future research should validate the application with larger and more diverse samples, including farmers and researchers engaged in carbon assessment aligned with Thailand Greenhouse Gas Management Organization (TGO) procedures. Additional testing should also extend to other economically important tree species cultivated in Thailand (e.g., rambutan, durian, mangosteen, and longkong), prioritizing cases where TGO-certified allometric equations are available to ensure methodological consistency and reporting credibility. Finally, integrating mobile-device LiDAR for tree measurement, coupled with near real-time carbon tracking, represents a promising pathway to improve accuracy, efficiency, and user experience ultimately strengthening farmers' capacity to conduct reliable carbon assessments independently and to support community-based forest carbon management.

6. Declarations

6.1. Author Contributions

Conceptualization, P.S. and N.K.; methodology, P.S. and N.K.; software, P.S. and N.K.; validation, P.S., N.K., and M.W.; formal analysis, P.S., N.K., and M.W.; investigation, P.S., N.K., and P.H.; resources, P.S. and N.K.; data curation, P.S., N.K., M.W., and K.T.; writing—original draft preparation, P.S. and N.K.; writing—review and editing, P.S., N.K., M.W., K.T., and P.H.; visualization, P.S., N.K., M.W., N.S., and K.T.; supervision, P.S., N.K., M.W., and P.H.; project administration, P.S. and N.K. ; funding acquisition, P.S. All authors have read and agreed to the published version of the manuscript.

6.2. Data Availability Statement

The data presented in this study are available on request from the corresponding author.

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6.4. Institutional Review Board Statement

Ethical review and approval were waived for this study due to the decision of the Ethics Committee of Suan Sunandha Rajabhat University (Certificate Number: COE. 2-158/2025), which granted an exemption from review.

6.5. Informed Consent Statement

Not applicable.

6.6. Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

7. References

[1] Philander, S. G. (1999). EI Niño and La Niña predictable climate fluctuations. Reports on Progress in Physics, 62(2), 123–142. doi:10.1088/0034-4885/62/2/001.

[2] Timmermann, A., An, S. I., Kug, J. S., Jin, F. F., Cai, W., Capotondi, A., ... & Zhang, X. (2018). El Niño–southern oscillation complexity. Nature, 559(7715), 535-545. doi:10.1038/s41586-018-0252-6.

[3] Arunrat, N., Sereenonchai, S., Chaowiwat, W., & Wang, C. (2022). Climate change impact on major crop yield and water footprint under CMIP6 climate projections in repeated drought and flood areas in Thailand. Science of the Total Environment, 807, 150741. doi:10.1016/j.scitotenv.2021.150741.

[4] Supratid, S., & Aribarg, T. (2022). Climate Change Adaptation in Thailand. Climate Change Adaptation in Southeast Asia: Springer Singapore, 197–216. doi:10.1007/978-981-16-6088-7_10.

[5] Kiguchi, M., Takata, K., Hanasaki, N., Archevarahuprok, B., Champathong, A., Ikoma, E., ... & Oki, T. (2021). A review of climate-change impact and adaptation studies for the water sector in Thailand. Environmental Research Letters, 16(2), 023004. doi:10.1088/1748-9326/abce80.

[6] Petpongpan, C., Ekkawatpanit, C., & Kositgittiwong, D. (2020). Climate change impact on surface water and groundwater recharge in northern Thailand. Water (Switzerland), 12(4), 1029. doi:10.3390/W12041029.

[7] Petpongpan, C., Ekkawatpanit, C., Visessri, S., & Kositgittiwong, D. (2021). Projection of hydro-climatic extreme events under climate change in Yom and Nan river basins, Thailand. Water (Switzerland), 13(5), 1–20. doi:10.3390/w13050665.

[8] Yang, S., Zhao, B., Yang, D., Wang, T., Yang, Y., Ma, T., & Santisirisomboon, J. (2023). Future changes in water resources, floods and droughts under the joint impact of climate and land-use changes in the Chao Phraya basin, Thailand. Journal of Hydrology, 620, 129454. doi:10.1016/j.jhydrol.2023.129454.

[9] Office of the National Economic and Social Development Council. (2023). The 13th National Economic and Social Development Plan (2023–2027). Office of the National Economic and Social Development Council, Bangkok, Thailand.

[10] UN General Assembly. (2015). Transforming our world: The 2030 Agenda for Sustainable Development (Resolution A/RES/70/1). United Nations, United States. Available online: https://www.refworld.org/legal/resolution/unga/2015/en/111816 (accessed on January 2026).

[11] Apipoonyanon, C., Kuwornu, J. K. M., Szabo, S., & Shrestha, R. P. (2020). Factors influencing household participation in community forest management: evidence from Udon Thani Province, Thailand. Journal of Sustainable Forestry, 39(2), 184–206. doi:10.1080/10549811.2019.1632211.

[12] Boonkird, S. A., Fernandes, E. C. M., & Nair, P. K. R. (1985). Forest villages: an agroforestry approach to rehabilitating forest land degraded by shifting cultivation in Thailand. Agroforestry Systems, 2(2), 87–102. doi:10.1007/BF00131268.

[13] Saengsanga, T., Kaewthani, S., & Rattana, T. (2024). Plant Diversity, Traditional Utilization, and Community-Based Conservation of the Small-Scale Nong Sakae Community Forest in Nakhon Ratchasima, Thailand. Forest and Society, 8(1), 179–194. doi:10.24259/fs.v8i1.31433.

[14] Thammanu, S., Han, H., Ekanayake, E. M. B. P., Jung, Y., & Chung, J. (2021). The impact on ecosystem services and the satisfaction therewith of community forest management in northern Thailand. Sustainability (Switzerland), 13(23), 13474. doi:10.3390/su132313474.

[15] Thammanu, S., Han, H., Marod, D., Zang, L., Jung, Y., Soe, K. T., ... & Chung, J. (2021). Non-timber forest product utilization under community forest management in northern Thailand. Forest Science and Technology, 17(1), 1-15. doi:10.1080/21580103.2020.1862712.

[16] FOR/AGR. (2025). Calculation for carbon sequestration. Thailand Greenhouse Gas Management Organization. Forest and Agriculture Project (FOR/AGR), Bangkok, Thailand. Available online: https://ghgreduction.tgo.or.th/th/tver-method/tver-tool/for-agr/item/3451-calculation-for-carbon-sequestration.html (accessed on January 2026).

[17] Shao, T., Qu, Y., & Du, J. (2022). A low-cost integrated sensor for measuring tree diameter at breast height (DBH). Computers and Electronics in Agriculture, 199, 107140. doi:10.1016/j.compag.2022.107140.

[18] Sheng, Y., Zhao, Q., Wang, X., Liu, Y., & Yin, X. (2024). Tree Diameter at Breast Height Extraction Based on Mobile Laser Scanning Point Cloud. Forests, 15(4), 590. doi:10.3390/f15040590.

[19] Sullivan, M. J., Lewis, S. L., Hubau, W., Qie, L., Baker, T. R., Banin, L. F., ... & Phillips, O. L. (2018). Field methods for sampling tree height for tropical forest biomass estimation. Methods in Ecology and Evolution, 9(5), 1179-1189. doi:10.1111/2041-210X.12962.

[20] Li, S., Fang, L., Sun, Y., Xia, L., & Lou, X. (2023). Development of Measuring Device for Diameter at Breast Height of Trees. Forests, 14(2), 192. doi:10.3390/f14020192.

[21] Zhao, K., Li, S., Wang, J., Sun, L., Fang, L., & Ji, J. (2024). Development and Application of Tree Radial Measurement Device. Forests, 15(10), 1710. doi:10.3390/f15101710.

[22] Ahamed, A., Foye, J., Poudel, S., Trieschman, E., & Fike, J. (2023). Measuring Tree Diameter with Photogrammetry Using Mobile Phone Cameras. Forests, 14(10), 2027. doi:10.3390/f14102027.

[23] Zhang, Q., Sun, Y., Zheng, X., Zhang, S., & Fang, L. (2023). Development of a Real-Time Continuous Measurement System for Tree Radial Direction. Forests, 14(9), 1876. doi:10.3390/f14091876.

[24] Butler, S. M., Schelhas, J., & Butler, B. J. (2020). Minority family forest owners in the United States. Journal of Forestry, 118(1), 70–85. doi:10.1093/jofore/fvz060.

[25] Catanzaro, P., & Markowski-Lindsay, M. (2022). Expanding Family Forest Owner Options to Keep Their Land in Forest Use. Journal of Forestry, 120(2), 208–221. doi:10.1093/jofore/fvab052.

[26] Poudyal, N. C., Butler, B. J., & Hodges, D. G. (2019). Spatial analysis of family forest landownership in the southern United States. Landscape and Urban Planning, 188, 163–170. doi:10.1016/j.landurbplan.2018.10.018.

[27] Alwashmi, M. F., Hawboldt, J., Davis, E., & Fetters, M. D. (2019). The iterative convergent design for mobile health usability testing: Mixed-methods approach. JMIR MHealth and UHealth, 7(4), 11656. doi:10.2196/11656.

[28] Hyzy, M., Bond, R., Mulvenna, M., Bai, L., Dix, A., Leigh, S., & Hunt, S. (2022). System Usability Scale Benchmarking for Digital Health Apps: Meta-analysis. JMIR MHealth and UHealth, 10(8), 37290. doi:10.2196/37290.

[29] Oliveira, E. R., Branco, A. C., Carvalho, D., Sacramento, E. R., Tymoshchuk, O., Pedro, L., Antunes, M. J., Almeida, A. M., & Ramos, F. (2022). An Iterative Process for the Evaluation of a Mobile Application Prototype. SN Computer Science, 3(4), 262. doi:10.1007/s42979-022-01153-6.

[30] Strandell-Laine, C., Leino-Kilpi, H., Löyttyniemi, E., Salminen, L., Stolt, M., Suomi, R., & Saarikoski, M. (2019). A process evaluation of a mobile cooperation intervention: A mixed methods study. Nurse Education Today, 80, 1–8. doi:10.1016/j.nedt.2019.05.037.

[31] Shen, Y., Wang, S., Shen, Y., Tan, S., Dong, Y., Qin, W., & Zhuang, Y. (2024). Evaluating the Usability of mHealth Apps: An Evaluation Model Based on Task Analysis Methods and Eye Movement Data. Healthcare (Switzerland), 12(13), 1310. doi:10.3390/healthcare12131310.

[32] Wills, J., Byham-Gray, L., Rothpletz-Puglia, P., Sangmo, T., Rosen, T., Williams, S., Suaray, M., & Rawal, S. (2025). Usability and acceptability of a mobile application prototype for managing hypertensive disorders of pregnancy: A mixed methods evaluation. Preventive Medicine Reports, 55. doi:10.1016/j.pmedr.2025.103108.

[33] Luo, S., & Botash, A. S. (2020). Testing a mobile app for child abuse treatment: A mixed methods study. International Journal of Nursing Sciences, 7(3), 320–329. doi:10.1016/j.ijnss.2020.06.008.

[34] Stabile, A. J., Iribarren, S., Sonney, J., Demiris, G., & Schnall, R. (2024). Usability testing of a mobile health application to support individuals with active tuberculosis: a mixed methods study. Informatics for Health and Social Care, 49(2), 136–148. doi:10.1080/17538157.2024.2333379.

[35] Gülci, S., Yurtseven, H., Akay, A. O., & Akgul, M. (2023). Measuring tree diameter using a LiDAR-equipped smartphone: a comparison of smartphone- and caliper-based DBH. Environmental Monitoring and Assessment, 195(6), 678. doi:10.1007/s10661-023-11366-8.

[36] Howie, N. A., & De Stefano, A. (2024). Measuring Tree Diameter Using LiDAR Equipped iPad: An Evaluation of Forest Scanner and Arboreal Forest Applications. Forest Science, 70(4), 304–310. doi:10.1093/forsci/fxae017.

[37] Sandim, A., Amaro, M., Silva, M. E., Cunha, J., Morais, S., Marques, A., Ferreira, A., Lousada, J. L., & Fonseca, T. (2023). New Technologies for Expedited Forest Inventory Using Smartphone Applications. Forests, 14(8), 1553. doi:10.3390/f14081553.

[38] Magnuson, R., Erfanifard, Y., Kulicki, M., Gasica, T. A., Tangwa, E., Mielcarek, M., & Stereńczak, K. (2024). Mobile Devices in Forest Mensuration: A Review of Technologies and Methods in Single Tree Measurements. Remote Sensing, 16(19), 3570. doi:10.3390/rs16193570.

[39] Wang, X., Singh, A., Pervysheva, Y., Lamatungga, K. E., Murtinová, V., Mukarram, M., Zhu, Q., Song, K., Surový, P., & Mokroš, M. (2021). Evaluation of IPAD Pro 2020 Lidar For Estimating Tree Diameters in Urban Forest. ISPRS Annals of the Photogrammetry, Remote Sensing and Spatial Information Sciences, 8(4/W1-2021), 105–110. doi:10.5194/isprs-annals-VIII-4-W1-2021-105-2021.

[40] Ogawa, H., Yoda, K., Ogino, K. and Kira, T. (1965) Comparative ecological studies on three main types of forest vegetation in Thailand II. Plant biomass. Natural and life in Southeast Asia, 4, 49-80.

[41] Eggleston, H. S., Buendia, L., Miwa, K., Ngara, T., & Tanabe, K. (2006). 2006 IPCC Guidelines For National Greenhouse Gas Inventories. Intergovernmental Panel on Climate Change (IPCC), Hayama, Japan.

[42] T-VER-S-TOOL-01-01 (2023). Calculation for carbon sequestration in tree. (Version 01). Thailand Greenhouse Gas Management Organization (Public Organization), Bangkok, Thailand. Available online: https://ghgreduction.tgo.or.th/th/tver-method/tver-tool/for-agr/download/6057/3451/23.html (accessed on January 2026).

[43] Islam, M. N., Khan, S. R., Islam, N. N., Rezwan-A-Rownok, M., Zaman, S. R., & Zaman, S. R. (2021). A Mobile Application for Mental Health Care During COVID-19 Pandemic: Development and Usability Evaluation with System Usability Scale. Advances in Intelligent Systems and Computing, 1321, 33–42. doi:10.1007/978-3-030-68133-3_4.

[44] Mclellan, S., Muddimer, A., & Peres, S. C. (2012). The Effect of Experience on System Usability Scale Ratings. Journal of Usability Studies, 7(2), 56–67.

[45] Lewis, J. R., & Sauro, J. (2018). Item Benchmarks for the System Usability Scale. Journal of Usability Studies, 13(3), 158–167.

[46] Mol, M., Van Schaik, A., Dozeman, E., Ruwaard, J., Vis, C., Ebert, D. D., Etzelmueller, A., Mathiasen, K., Moles, B., Mora, T., Pedersen, C. D., Skjøth, M. M., Pensado, L. P., Piera-Jimenez, J., Gokcay, D., Ince, B. Ü., Russi, A., Sacco, Y., Zanalda, E., … Smit, J. H. (2020). Dimensionality of the system usability scale among professionals using internet-based interventions for depression: A confirmatory factor analysis. BMC Psychiatry, 20(1), 218. doi:10.1186/s12888-020-02627-8.

[47] Khan, Q., Hickie, I. B., Loblay, V., Ekambareshwar, M., Zahed, I. U. M., Naderbagi, A., Song, Y. J. C., & LaMonica, H. M. (2025). Psychometric evaluation of the System Usability Scale in the context of a childrearing app co-designed for low- and middle-income countries. Digital Health, 11, 20552076251335412. doi:10.1177/20552076251335413.

[48] Guest, G., Bunce, A., & Johnson, L. (2006). How Many Interviews Are Enough?: An Experiment with Data Saturation and Variability. Field Methods, 18(1), 59–82. doi:10.1177/1525822X05279903.

[49] Hennink, M. M., Kaiser, B. N., & Marconi, V. C. (2017). Code Saturation Versus Meaning Saturation: How Many Interviews Are Enough? Qualitative Health Research, 27(4), 591–608. doi:10.1177/1049732316665344.

[50] Filiana, A., Rini, M. N. A., & Prabawati, A. G. (2023). Usability Analysis of "SiPasar", a Web-Based Application for Mapping Traditional Markets in Yogyakarta. 2023 8th International Conference on Informatics and Computing, ICIC 2023, 1–6. doi:10.1109/ICIC60109.2023.10382036.

[51] Permana, P. A. G., Dewanti, P., & Santika, K. Y. (2024). Analysis of Sports Match Charts and Scoring Applications Based on Website and Mobile Using the System Usability Scale Method. 2024 6th International Conference on Cybernetics and Intelligent System, ICORIS 2024, 1–6. doi:10.1109/ICORIS63540.2024.10903865.

[52] Lewis, J. R. The system usability scale: past, present, and future. International Journal of Human–Computer Interaction, 34(7), 577–590.