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What's causing the biochar adoption gap? Practitioner reflections on perceived barriers and opportunities among smallholder farmers in Southeast Asia

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While Biochar demonstrates agronomic potential for soil improvement, crop productivity, and carbon sequestration, limited research has examined adoption patterns and implementation barriers among small-scale farmers through a sustainability lens. Employing a qualitative self-study design, this community case study reflects upon biochar extension programming delivered by Civil Society Organization (CSO) extension practitioners across Southeast Asia. Authors found that despite biochar's consistently high interest among learners and established scientific merit, sustained, multiseason adoption among smallholder farmers remains limited. Observed patterns that constrain adoption across several Southeast Asian countries include the labor necessary to produce recommended volumes at the artisanal kiln scale, and significant opportunity costs within small-scale farming systems. Successful, sustained adoption generally emerged from two contexts: 1) strategic and intensive horticultural applications, such as within greenhouse, nursery, and small plot production settings, and 2) enterprise operations with a pre-existing biomass waste management problem, uniformly sized feedstock, and sufficient scale to access carbon credit markets. Practitioner reflections suggest that effective biochar extension programming should clearly communicate biochar's realistic agronomic benefits and timelines, and better target their programming toward high-return applications or as an enterprise development opportunity rather than in promoting biochar production and soil incorporation as a universally applicable, farm-level practice among small-scale farmers.

KEYWORDS
adoption, agroecology, biochar, extension & advisory services, Civil Society Organization, smallholder adaptation, soil health, sustainable agriculture

1 Introduction

Biochar is a carbon-rich material derived from the pyrolysis of biomass, such as agricultural and forestry byproducts, under limited oxygen conditions. Rather than being used as fuel-like charcoal for energy, biochar is applied as a soil amendment to improve soil health and sequester carbon. Its agroecological properties have been widely studied in relation to crop productivity, soil health, and climate change mitigation (Premalatha et al., 2023; Biederman and Harpole, 2013).

Meta-analyses of biochar studies have shown that biochar can have a small but statistically significant impact on crop productivity as a result of improvements in soil quality (Xu et al., 2021; Jeffery et al., 2011), contributing to resilience and SDG 1 and 2. This is largely attributable to the high micro-porosity of biochar, which improves mycorrhizal colonization, cation and anion exchange capacity, water holding capacity, and nutrient retention (Oni et al., 2019). Biochar also tends to have a high pH, which makes it valuable as a soil amendment in acidic soils (Schmidt et al., 2021). Certain kinds of biochar are also highly capable of immobilizing heavy metals in solid through adsorption (Ma et al., 2026; Viotti et al., 2024). However, its impact is highly dependent on factors such as existing soil pH and texture, biochar C:N ratio, and application rate (Xu et al., 2021; Jeffery et al., 2011). This variability makes it challenging to provide good recommendations for biochar as a soil amendment. Research is ongoing to determine the most effective and economical applications of biochar in unique contexts to improve food system sustainability.

Studies have also shown that biochar could have a significant impact in reducing global warming potential through mitigation by increasing soil organic carbon, enhancing adsorption, and creating an environment conducive to healthy soil microbial growth (Xu et al., 2021; Sugiarto et al., 2021), contributing to SDG 13. This occurs through transforming the carbon within feedstock biomass into a durable form Owsianiak et al. (2021) found that pyrolysis technologies, especially gasifiers, provided more environmental benefits than composting due to their carbon storage capacity. Biochar production and incorporation into soil is one of the few methods of carbon sequestration possible on a smaller scale. Furthermore, it can offer an alternative to open field burning, which disperses unhealthy volumes of PM2.5 particles into the atmosphere. Taken together, the literature suggests that biochar “can offer [a]‘tripartite win–win’ for crop yield, [soil organic carbon] enhancement, and greenhouse gas mitigation in some contexts” (Xu et al., 2021).

While the scientific merit of biochar is well-studied, existing adoption literature on biochar is heavily quantitative and focused at the farmer level, investigating individual-level correlates of adoption. Qualitative, exploratory scholarship among change agents with wide exposure to farmers in different adopter categories (i.e., innovators, early adopters, late adopters, laggards [Rogers, 2003]) is lacking. This gap risks missing significant cultural, structural, and contextual barriers to adoption that could prevent uptake among small-scale farmers. This study seeks to address this gap through a qualitative self-study of professional practice case study (LaBoskey, 2004). Through reflecting on the perspectives of NGO workers who represent change agents providing agricultural advisory services across Southeast (SE) Asian countries (specifically, Thailand, Myanmar, Cambodia, the Philippines, and Laos), the authors seek to identify themes representing barriers and opportunities to biochar adoption among small-scale farmers in the region.

2 Methods

This community case study employed a qualitative self-study of professional practice (SSP) design (LaBoskey, 2004) to examine the training and adoption of biochar innovations in SE Asia. Self-study is characterized by its focus on improving professional practice through systematic, critical reflection by practitioner-researchers. This study is self-initiated, and improvement-aimed, while also grounded in transparency and reflexivity (LaBoskey, 2004). This approach was appropriate given that the researchers were directly embedded within the biochar training and dissemination processes and sought to critically examine their own roles in shaping adoption outcomes.

2.1 Case study context

The study was situated within the ECHO Asia regional network, centered at the Asia Impact Center in Chiang Mai, Thailand, with programmatic reach extending across SE Asia. The case focused on biochar training initiatives, extension strategies, and subsequent engagement with network members and small-scale farmers.

2.2 Participants (self as researcher)

Consistent with self-study methodology, the participants were the authors themselves, acting as practitioner-researchers. The authors collectively bring 45 years of experience in agricultural extension, training, and program implementation across SE Asia. Their roles included designing and facilitating biochar trainings, engaging with partner organizations, and supporting follow-up extension activities. The authors positioned themselves as both subjects and analysts of the research, acknowledging their dual roles and the need for critical examination of their assumptions, decisions, and practice (Hamilton and Smith, 2008).

2.3 Data collection

Self-study research emphasizes the use of multiple, complementary data sources to support rigor and trustworthiness. In accordance with this, the study drew on the following:

1. Reflective Practice

The primary data source consisted of reflective accounts generated by the authors. Reflections focused on instructional practices and observed adoption behaviors.

2. Field-Based Observations

The authors incorporated participant observation from biochar training events, workshops, and follow-up engagements. Observations included both structured training environments and informal interactions with trainees and partners, providing insight into real-world application and constraints.

3. Program Documentation

Internal program records, such as training curricula, instructional materials, and post-training evaluation surveys, were analyzed to contextualize reflective insights. Post-training evaluation is conducted by ECHO at the completion of a training event. These evaluations focused on perceptions of training quality rather than objective assessments of knowledge acquisition. Training outcomes have historically been assessed through these trainee satisfaction surveys. In the case of biochar trainings, ECHO Asia has post-training evaluations over the last 3 years where our biochar training consistently scores around a 4-5 on a 5-point Likert scale, showing high satisfaction on content, trainers, value, etc.

3 Informal and relational data

Consistent with practitioner inquiry, the study also drew on informal interactions with network members and partners. These interactions, occurring through ongoing communication and collaboration, contributed to a longitudinal understanding of adoption patterns. While ECHO does not have post-training follow-up survey data on adoption, it maintains frequent contact with its partners. Adoption tracking occurs mainly through follow-up interactions and has been informal and relational. Repeated interaction with ECHO's partners through continued training of their project participants and staff allows for a strong feedback loop. Much of the anecdotal evidence reported in this article comes from one rapid adoption assessment conducted in mid 2025 across Thailand, Laos, and the Philippines. This was conducted through semi-structured interviews with opportunistic sampling of ECHO network members regarding adoption and their ongoing technical resourcing needs.

3.1 Data analysis

Data were analyzed using iterative thematic analysis, consistent with self-study research practices. The process involved:

1. Individual reflection by each author
2. Collaborative dialogue on the article to compare interpretations and challenge assumptions
3. Development of shared themes related to diffusion of innovation

Dialogic validation was used as a central analytic strategy, in which the authors engaged in a critical conversation about the article to interrogate their interpretations and reduce unchecked bias (Hamilton and Smith, 2008). Analysis was further informed by diffusion of innovation theory, particularly focusing on perceived characteristics of innovations (relative advantage, complexity, and compatibility) as analytical lenses (Rogers, 2003). In alignment with the criteria for rigor in self-study research outlined by LaBoskey (2004), several approaches were used to enhance the study's trustworthiness. Transparency was established by acknowledging the researchers' roles and positionality within the project. Systematic inquiry was conducted through structured reflection processes and multiple data sources. Triangulation was utilized by integrating reflections, observations, and program documentation from multiple practitioners, as well as by comparing firsthand accounts with existing peer-reviewed scholarship. As previously mentioned, Dialogic validation occurred through collaborative critique and discussion among the authors to refine interpretations and challenge assumptions. Finally, the study maintained an aim on improvement by generating actionable insights to strengthen future training and extension practice.

4 About the program

ECHO, Inc., is an international Civil Society Organization (CSO), with agricultural centers in SE Asia, East Africa, West Africa, and Central America and Caribbean, emphasizing agroecosystem strategy identification, co-creation, validation, dissemination, and evaluation of agricultural innovations and strategies (Figure 1) through multiple channels, including research, training events, demonstration plots, publications, digital platforms, and regional networks, to ensure that knowledge is communicated in accessible and contextually relevant formats that promote peer-to-peer learning and replication. ECHO prioritizes identifying "options for farmers" rather than prescriptive interventions, enabling producers to adapt innovations to local socioecological and economic conditions and strengthen household- and community-level resilience. In addition, ECHO often disseminates options in collaboration with a network of change agencies and change agents, including other CSOs, researchers, extension professionals, faith-based organizations, and community leaders, using a Co-creation and Training-of-Trainers model. These change agencies then reach small-scale farming communities.

This case study will focus on the uptake and adoption of biochar innovations in SE Asia, where the ECHO Asia Impact Center is located. This scope was chosen because ECHO Asia is ECHO's longest-running regional center (17 years), was the first center to be introduced to biochar as a new innovation (in 2011), and SE Asia has a high prevalence of acidic and degraded soils. SE Asia is particularly prevalent in acrisols and ferrasols, both of which are characterized by high levels of weathering and acidity (Omondi et al., 2016). Furthermore, in the absence of biomass cycling land management practices, agricultural soils have low organic matter content. Biochar tends to have the largest positive impact on yield improvements in these kinds of degraded, acidic soils with low organic matter found abundantly in SE Asia (Premalatha et al., 2023; Biederman and Harpole, 2013). While data on biochar's impact on crop productivity globally is highly variable, its impacts are positive in conditions prevailing in SE Asia compared to temperate climates. Given these conditions, it would be expected that SE Asia would experience rapid uptake of such an innovation compared to other regions of the world.

Among a diverse network of partners, ECHO also works closely with the Warm Heart Foundation, a community-led development organization based 90 km Northeast of Chiang Mai, Thailand, also engaged in the extension programming of biochar among smallholder farmers. In addition, Warm Heart operates Biochar Life, which oversees the processes and procedures necessary to verify and certify artisanal-scale biochar production for carbon credits. Warm Heart has created processes and procedures to permit certification of biochar produced and used by smallholders, and has trained over 20,000 individuals about biochar in Thailand and East Africa. Warm Heart's smallholder-appropriate kilns have been shared with ECHO and ECHO's global network members through conferences, events, and direct referrals.

ECHO operates Small Farm Resource Centers in different regions of the world, including Thailand, as informal extension hubs offering underserved stakeholders innovative agricultural options and appropriate technologies (Bicksler et al., 2022). From the ECHO Asia Small Farm Resource Center, and into surrounding sites, ECHO's extension efforts have offered biochar co-creation and training at a variety of on-farm workshops, conferences, and other training events for 14 years. 435 individuals were trained about biochar between March 2024 and October 2025, with an average of 15.7 h of instruction/demonstration per individual.

ECHO Asia offers highly tailored training depending on the group of trainees. The typical training delivered at ECHO Asia's Impact Center in Chiang Mai is described below. Some biochar training happens off-site, and typically focuses on the practical application and demonstrates fewer kiln types. Some groups have lower levels of education, and the theoretical/scientific components of the training are simplified.

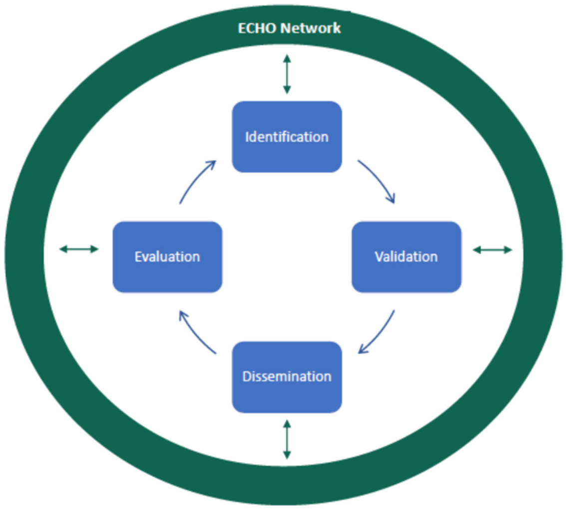

FIGURE 1
Visual depiction of ECHO's method of identifying, validating, disseminating, and evaluating agroecosystem strategies alongside ECHO's network.

4.1 Training specifics

Typical to ECHO Asia training events, biochar training provides participants with a structured introduction to the scientific principles, production processes, and practical applications of biochar. Following this, practical demonstrations are given followed by a closing classroom session for remaining questions to be answered.

Instruction begins with an elicitation of prior knowledge through peer discussion, prompting participants to define biochar in their own terms before transitioning into formal content. The sessions establish that biochar formation relies on pyrolysis, defined as the thermal decomposition of biomass in an oxygen-limited environment, thereby minimizing CO_2 and PM2.5 emissions and conserving carbon in a stable solid form.

Participants are introduced to the defining characteristics of biochar, including its high porosity, substantial specific surface area, and long-term chemical stability in soil. Biochar's relevance in agricultural and environmental systems forms the next instructional segment. The training emphasizes the role of biochar in ameliorating degraded soils, improving water-use efficiency, supporting soil microbial communities, regulating soil acidity, and reducing pollutant concentrations. Beyond soil applications, biochar is presented as an effective filtration medium in water treatment systems and as a contributor to reduced atmospheric emissions when used as an alternative to open biomass burning. To reinforce these concepts, participants complete a short quiz covering biomass selection, pyrolysis fundamentals, biochar properties, and kiln types.

Immediately following the instructional portion, trainees engage in a hands-on practicum in which they produce biochar. This practical component allows participants to observe biochar creation and ask questions about the process. The training thus integrates scientific theory with experiential learning to provide a comprehensive understanding of biochar production and application.

Production technologies are explained through at least three comparative small-scale kiln designs and use: retort kilns, Top-Lit Updraft (TLUD) kilns, and Kon-Tiki kilns (see Figures 2-4). Each method is demonstrated step-by-step. For the TLUD and Kon-Tiki kilns, this includes top-lighting the biomass, formation of the downward-moving pyrolytic front, secondary combustion of released gases, maintenance of an oxygen-restricted char layer, and final quenching. Retort systems are demonstrated as closed-chamber alternatives in which biomass is heated indirectly within an airtight container. Some training groups also look at alternative methods, such as pit trench or traditional buried charcoal production techniques.

Participants are also introduced to the concept of "charging" biochar—pre-loading it with nutrients via compost or amendments—before incorporation into soil to avoid nutrient immobilization. Charging options demonstrated included soaking in a manure-liquid solution, mixing with fresh manure, while options to co-compost or age in soil are also highlighted. Technical resources created by ECHO Asia for training and educational purposes are housed on ECHOcommunity.org: http://edn.link/asiabiochar (ECHO community, 2025).

4.2 Key programmatic elements

Co-authors serving as ECHO Asia and Warm Heart international program staff, representing 45 years of combined agricultural advisory experience across SE Asia, have worked

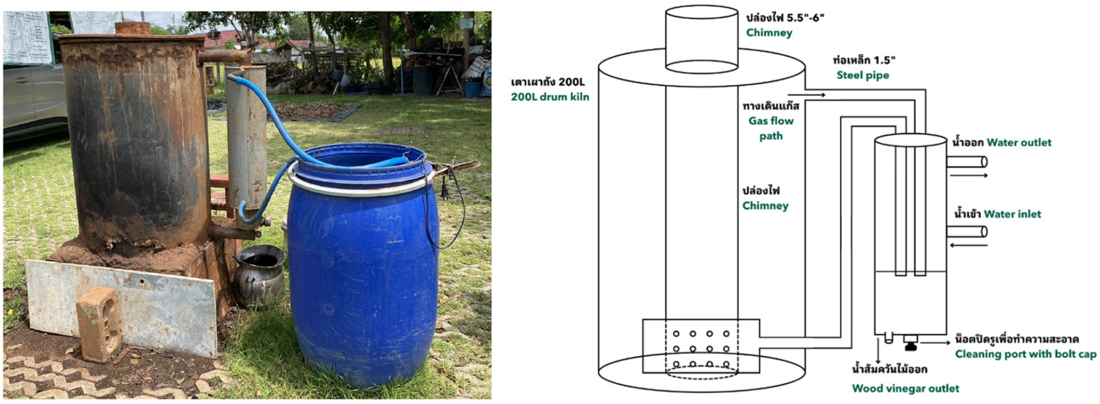

FIGURE 2
Retort kiln at ECHO Asia's Impact Center in Chiang Mai, Thailand, and diagram of a retort kiln (ECHO Asia staff).

directly with farmers, extension staff, and community leaders to disseminate knowledge on the use and application of biochar as a soil amendment and as a water filtration media. Together, they have trained hundreds of workshop participants on biochar production, both as a standalone topic and within a broader curriculum on sustainable agriculture.

The authors have seen a difference in the incentives and priorities of ECHO's target trainees, who are often change agents, and those of biochar end-users, who are often smallholder farmers. For example, a June 2025 survey of ECHO's network of change agents (development workers, missionaries, local religious institutions, local community organizations, research institutes, and international CSOs) indicates that biochar elicits high interest as an agricultural innovation among these groups. These change agents are interested in biochar primarily for its potential in environmental remediation, carbon capture, smoke reduction, and as a community-building activity. Reasonably high adoption rates, meaning sustained use over time, are estimated at 50% among the authors' recall of informal and relational follow-ups, which are a key feature of ECHO's strategy throughout the region. These groups include agricultural demonstration projects, research institutions and extension agencies, small-scale development workers, and eco-conscious lifestyle farmers. These actors typically produce biochar in TLUD, Kon-Tiki, or trench kilns, and apply biochar to smaller areas, such as small-scale vegetable plots. In northern Thailand, Warm Heart staff observed that those with sustained biochar adoption have been organic farmers seeking alternatives to synthetic inputs and reforestation initiatives. Campaigns seeking to address air quality issues caused by agricultural burning in SE Asia have also incorporated biochar into their strategies. It's important to note that the motivations of these groups are likely driven by the holistic set of co-benefits of biochar, which are often intangible, rather than by any immediate financial incentives from yield improvements.

In contrast, small-scale farmers themselves have generally not been interested in the longer-term impacts of biochar, such as carbon capture and soil remediation. While biochar has technical merit and generates strong interest among training participants per training endline surveys, its sustained, multiseason adoption among small-scale farmers in SE Asia remains very low in informal and relational follow-ups. This indicates that the disconnect occurs somewhere between interest and sustained implementation, and that feasibility constraints hinder adoption beyond the trial period among resource-constrained small-scale farmers. ECHO staff within SE Asia were able to recall less than five specific instances of a small-scale farmer's consistent use of biochar as a soil amendment after trialing the practice in their own production systems. The scant examples observed include the use of biochar rice husk as a potting mix in the Philippines, Cambodia, and Thailand to prepare a free-draining potting mix. Another instance was small-scale farmer in Banteay Meanchey, Cambodia, who was producing a biochar potting mix to propagate cucumber and tomato seedlings prior to transplanting them into his fields, having learned the technique from YouTube. Warm Heart staff in Thailand echoed these observations. Warm Heart staff conducted side-by-side rice trials in which farmers observed visible improvements in soil quality and increased earthworm populations in biochar-amended plots, yet still chose not to adopt biochar in their own production practices. The exceptions observed among Warm Heart practitioners have been young, tech-savvy organic farmers who were already seeking non-synthetic farm inputs.

Several variables may drive the divergence in adoption rates between the ECHO network (which often represents change agents) and small-scale farmers (target end users). These largely cluster around three of Rogers (2003) characteristics of innovations: relative advantage, complexity, and compatibility.

4.2.1 Relative advantage

Relative advantage refers to the degree to which an innovation is perceived as superior to the solution it replaces, often in terms of cost, efficiency, or social prestige (Rogers, 2003). The perceived relative advantage of biochar utilization is likely much lower for SE Asia small-scale farmers than for many change agents. A recent study showed that farmers' intention to adopt biochar is positively related to perceived usefulness, with its economic value proposition emerging as the most salient antecedent, followed by output quality, result demonstrability, and awareness of climate

FIGURE 3
A TLUD kiln at ECHO Asia's Impact Center in Chiang Mai, Thailand and diagram of a TLUD kiln (ECHO Asia staff).

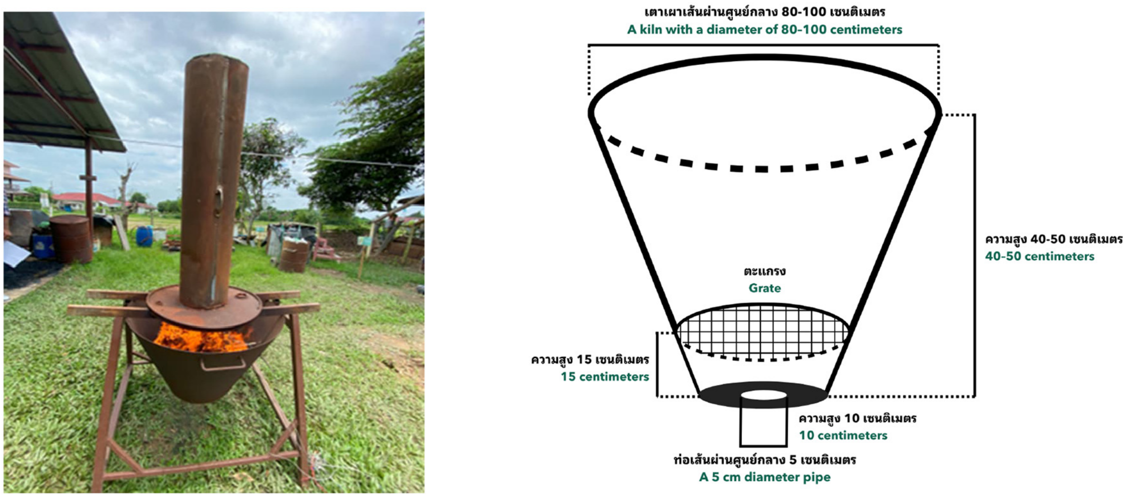

FIGURE 4
A Kon-Tiki kiln at ECHO Asia's Impact Center in Chiang Mai, Thailand and diagram of a Kon-Tiki kiln (ECHO Asia staff).

change (Perrone et al., 2025). The intangible co-benefits of carbon sequestration and long-term soil remediation are salient for many change agents in ECHO's network, but may not be perceived as immediately relevant by small-scale farmers. Given the challenge of practically producing large enough volumes at the small-scale farming level, it follows that the economic value proposition and resulting demonstrability would be negatively impacted, lowering perceived usefulness by small-scale farmers.

Other economic drivers also likely impact adoption– in northern Thailand, biochar adoption is hindered by the relatively low cost and accessibility of chemical fertilizers, which offer more immediate and less variable results. These are made widely accessible through well-established corporate field sales agents, who are often the farmers' only source of farming techniques. Warm Heart staff with experience across several sub-Saharan African countries observed that, in contrast, the unaffordability of chemical fertilizers in Africa often drove small-scale farmers to adopt biochar.

4.2.2 Complexity

Complexity refers to the degree to which an innovation is perceived as difficult to understand and use (Rogers, 2003). Biochar has a highly variable impact as a soil amendment, making its understanding complex. Several global meta-reviews on biochar's impact on yield have been conducted, and show that while the average yield increase is around 15% across trials, there are also trials that demonstrate a negative impact on yields (Premalatha et al., 2023; Biederman and Harpole, 2013; Schmidt et al., 2021). These negative impacts on yields can be caused by reduced plant uptake of key nutrients P, Ca, Mg, and Mn, as well as nutrient leaching and deficiencies at high biochar application rates (Regmi et al., 2022; Alazzaz et al., 2020). Furthermore, context-specific factors like feedstock type, pyrolysis temperature, soil pH, and soil salinity also contribute to biochar's impact variability (ibid.). Given the higher risks that small-scale farmers regularly contend with, it follows that this variability and potential short-term negative yield impacts would also hinder the perceived relative advantage and complexity in implementing biochar into production practices. Moreover, unlike chemical fertilizers, the benefits to soil structure improvements and greenhouse gas emissions are delayed and difficult to observe, in contrast to the immediate upfront labor costs of biochar production. These benefits are also complex, generally involve some understanding of soil science to appreciate, and may be more difficult to communicate to farmers with less formal education. Indeed, studies have shown that education levels have a positive and significant impact on biochar adoption rates (Kyalo and Mogaka, 2025; Janiszewska-Latterini et al., 2025).

The high volume of feedstock biomass required also poses a bottleneck for small-scale farmer adoption. For instance, in northern Thailand, feedstock (often crop residue) is often thinly dispersed across steep smallholdings with poor road access that make centralized collection expensive and unviable. Long seasons of high precipitation can also hinder the accumulation of dry feedstock for biomass and briquette production.

4.2.3 Compatibility

Compatibility refers to how consistent the innovation is with the existing values, past experiences, and needs of potential adopters (Rogers, 2003). There are several bottlenecks in biochar production related to compatibility that also likely contribute to low adoption rates among farmers in SE Asia. ECHO trainings usually incorporate artisanal-scale kilns, which take expertise, time, or money to build, creating an initial barrier to adoption. Higher adoption rates may be observed if kilns are donated or subsidized. Furthermore, biochar is time-consuming to make. Application rates in many studies are in tons per hectare, which is not feasible for small-scale farmers using the TLUD pyrolysis method that

FIGURE 5
ECHO Asia staff Songsan Lerdprakun incorporates biochar into a raised vegetable production plot **(left)** and ECHO Asia team rinsing biochar prior to installation in a water filter system **(right)**.

ECHO staff teach in workshops. For example, a farmer applying a recommended 5 tons/ha on a 152 sq m rice field would need to spend 20 h of labor and fill twenty 200-liter TLUD kilns worth of biomass (see Table 1 for more breakdowns on feedstock, burn time, and efficiency, based on repeated measurements by ECHO team members). Figures represent broad averages from farm tests and are only meant to illustrate the labor costs of field-level application.

Other, more context-specific factors also impact adoption rates. Aging farmer populations can hinder labor availability for additional production activities. Topography also likely impacts adoption rates in the uplands, as farmers are reluctant to carry large volumes of heavy inputs or equipment uphill.

4.2.4 Opportunities

Program observations indicate that biochar adoption increases when there are opportunities for intensive, strategic application rather than open field applications. Sustained, multiseason adopters have incorporated biochar into high-value, small-volume applications, such as those commonly used in horticultural practices. Examples of this include biochar in potting mixes for vegetable seedling production in greenhouse systems, as substrate amendments for fruit tree seedling propagation, within swales to slow erosion and increase water and nutrient retention in coffee farms, and incorporation into raised bed or kitchen garden systems. These instances allow small quantities of biochar to generate disproportionate value, where farmers can more immediately observe its impacts. Conversely, farmers attempting to produce biochar for open field application quickly abandon the pursuit due to the frustration of not producing enough volume. This volume constraint appears to be a key feasibility-limiting factor hindering small-scale farmer adoption in SE Asia.

Given this, it follows that other patterns of sustained, multiseason adoption are instances in which larger farms and enterprises already produce high volumes of biowaste, creating a pre-existing need for disposal options. Having a single, uniformly sized feedstock source may increase feasibility. Examples include regular pruning in longan (*Dimocarpus longan*) orchards in northern Thailand and centralized corn-shelling locations that produce piles of cobs. This suggests that biochar shows more promise as an "enterprisable waste management solution" implemented by entities with sufficient scale than as a feasible farmer-level practice. These larger entities can also generate enough biochar to participate in carbon credit markets, an economic incentive that is generally unavailable to small-scale farmers.

4.3 Practical implications and lessons learned

4.3.1 Targeting specific niches

Change agencies may achieve a greater impact among small-scale farmers if they target specific niches where adoption has proven more viable. These include more intensive, smaller-volume uses, such as bulking up media in high-quality potting mixes for greenhouse seedling trays and raised-bed vegetable production, and utility in biosand water filtration (Figure 5). Furthermore, adoption efforts in the region may be more effectively spent in identifying farms or agribusinesses with a large enough existing biowaste output and operational capacity to make biochar production economically viable and sold as a value-added product (e.g., briquettes, bottles of wood vinegar, bags of quality composts, and potting mixes). While this targeted approach may improve diffusion success, it may also exclude poorer households without the requisite land tenure and access to financial resources. CSOs should investigate aggregation models, such as cooperative kilns or biomass centralization strategies, to avoid reinforcing inequities. The authors do not recommend targeting biochar production for large scale application to open field crops use among small-scale farmers in SE Asia due to feasibility issues with producing sufficient volume to result in positive yield responses. Biochar production

TABLE 1 Breakdown of different labor requirements and efficiency rates of common feedstocks.

Feedstock	Burn time (per 200-liter TLUD kiln)	Temperature range	Mass to fill kiln	Feedstock to biochar mass efficiency
Bamboo	1 h 15 min	300-730°C	27.0 kg bamboo	3.4 kg yield, 13% efficiency
Wood	1 h 40 min	250-680°C	38.2 kg wood	5.4 kg yield, 14.1% efficiency
Corn cobs	1 h	400-750°C	22.0 kg corn cobs	3.9 kg yield, 17.7% efficiency

for highly intensive horticulture, kitchen gardens, or potted plants is more likely to result in observable production increases with feasible application rates. The authors also do not recommend biochar production when biomass aggregation is labor intensive, for example when biomass is collected from decentralized sources, steep terrain, or under labor scarcity.

4.3.2 Training approach

The observations suggest a need for some programmatic adjustments in extension and CSO programs that offer biochar training in SE Asia. Firstly, a reassessment of which kilns are promoted is warranted. The kiln type currently featured in ECHO's training events produces high-quality biochar, but at a high labor cost that is often prohibitive to small-scale farmers. Whereas this kiln is good for high-quality char for sorption in water filtration applications, it may not make sense for soil amendment applications. Warm Heart practitioners raised a need for a straightforward decision-making guide on which kilns and biochar production techniques are ideal for their context (e.g., terrain, farmer labor, target application).

Secondly, training content should very clearly frame biochar as a soil amendment that provides benefits to soil structure and increased pH, thereby contributing to long-term soil health (and hence, resilience). Biochar trainings must include methods of charging biochar with organic matter (compost, urine, manure, etc.) to complement its soil amending properties with slow-release fertilization. Third, communication materials should be produced on biochar production and usage that are simple and farmer-focused. Program messaging should also be realistic about feasible uses. Instead of promoting biochar as a broadly applied soil amendment, extension providers and change agents should focus on where it is most viable and has adoption potential, such as in small-scale kitchen gardening, on highly degraded acidic soils with poor structure, for potting soil, in water filtration, or where farmers have ready access to existing sources of biowaste appropriate for pyrolysis (e.g. rice husks). Biochar has many potential applications that are innovative and can contribute holistically to resilience and toward ecosystem-based solutions, contributing to multiple SDGs simultaneously.

To support the diffusion and adoption of biochar, CSOs should consider working with change agencies to both train community opinion leaders and learn from local biochar innovators. Effort should also be made to identify key opinion leaders (i.e., local champions) as trainers, as this has encouraged small-scale farmer adoption in East Africa, per Warm Heart's experience.

5 Limitations

This case study reflects upon and synthesizes practitioner experience in delivering biochar training and adoption across SE Asia. Consequently, several methodological limitations must be acknowledged.

As a self-study, the reflections are shaped by the authors' perspectives rather than by systematic data collection, making them subject to observer bias, selective interpretation, and self-selection. Although dialogic validation was employed to mitigate the risks of observer bias and selective interpretation, the absence of external data sources limits generalizability. Additionally, reliance on informal and anecdotal evidence constrains the ability to draw causal inferences regarding adoption outcomes. The participants at both ECHO Asia and Warm Heart biochar trainings are also self-selected, representing those already interested in sustainable agricultural innovations and improvements. Their experiences and circumstances may differ from those of non-participants, thus also limiting the generalizability of the reflections presented here. Agronomic performance was not measured in this study; consequently, all recommendations are based on reflections on feasibility and adoption behaviors, rather than on yield and soil outcomes.

5.1 Future research

Future research should examine the factors influencing biochar adoption among small-scale farmers in SE Asia, as well as the biochar technologies and processes used to produce it. Research should build on this paper's perspectives, using more rigorous methodologies to investigate the observations presented in this study.

The findings indicate that while ECHO's multi-channel dissemination model has been effective in generating awareness and technical competence among change agents, a systematic assessment of adoption and sustained use among end users remains an important next step. CSO monitoring and evaluation efforts should move beyond measuring training reach and participant interest to more rigorously examining patterns of uptake, adoption, and discontinuance among small-scale farmers. Incorporating a monitoring framework that tracks perceived usefulness, economic returns, labor requirements/constraints, and reinvention over time would help CSOs better understand where and why adoption occurs or falters among intermediaries and farmers. We propose that key indicators that should be included are a) the percentage of small-scale farmers trained that still using the practice after one season and b) self-reported labor change, which measures how much incorporating biochar increased, decreased, or did not change workloads. Care should be taken to closely monitor the gender-disaggregated outcomes of these indicators to monitor both potential income-generating opportunities for women or threats in the form of drudgery and increased labor burden.

5.1.1 Future qualitative, participatory research directions

Participatory action research (PAR) that engages small-scale farmers as co-investigators and co-creators should be carried out to provide deeper insights into target end-use decision-making priorities and barriers that are difficult to capture with outsider, observational approaches. These should include not only questions that gauge innovation and audience characteristics, but also identify the biggest structural barriers to implementation. Various digital extension tools and community-of-practice models should be compared and studied to identify which follow-up interventions can most effectively support sustained biochar adoption. Finally, future efforts are needed to develop context-specific guidance on kiln selection and production methods, informed by local terrain, biomass availability, labor capacity, and intended use.

5.1.2 Future quantitative research directions

Future research conducting long-term cost–benefit analyses is needed to quantify and compare the labor and financial trade-offs of biochar-based soil management with conventional fertilizer use over multiple seasons. More multi-year agronomic trials are needed to assess the long-term effects on soil fertility and crop productivity when using farmer-practical, small-scale application methods. Finally, research on low-cost feedstock drying methods and standardized briquette quality could improve production efficiency and marketability, supporting broader adoption and reduced deforestation.

Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

Author contributions

MH: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Project administration, Validation, Visualization, Writing – original draft, Writing – review & editing. SS: Conceptualization, Data curation, Investigation, Methodology, Project administration, Supervision, Validation, Writing – original draft, Writing – review & editing, Resources, Visualization. AB: Conceptualization, Funding acquisition, Project administration, Resources, Supervision, Validation, Writing – review & editing, Methodology. BF: Conceptualization, Formal analysis, Investigation, Methodology, Visualization, Writing – original draft, Writing – review & editing. SS: Investigation, Methodology, Resources, Validation, Writing – review & editing, Project administration. PT: Conceptualization, Investigation, Project administration, Resources, Supervision, Writing – review and editing, Methodology, Validation. ES: Formal analysis, Investigation, Validation, Writing – review & editing, Methodology. MS: Formal analysis, Investigation, Validation, Writing – review & editing, Methodology.

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