Environmentally-appropriate technology under lack of resources and knowledge: Solar-powered cocoa dryer in rural Nias, Indonesia

Corthias P.M. Sianipar a,b,*

a Division of Environmental Science and Technology, Kyoto University, Kyoto, 606-8502, Japan
b Department of Global Ecology, Kyoto University, Kyoto, 606-8501, Japan

ARTICLE INFO

Keywords:
Technological appropriateness
Environmental design
Knowledge gap
Economic constraint
Solar drying
Renewable energy
Appropriate Technology
Indigenous knowledge
Community empowerment

ABSTRACT

Climate change has substantially affected rural areas, considering their lack of resources and knowledge. In general, new technologies claim to produce fewer environmental impacts to adapt to climatic changes. Still, they typically emerge at the expense of higher investments and the technical knowledge required. However, the economic and knowledge constraints of rural areas make it challenging to employ expensive and sophisticated environment-friendly technologies. This study aims to propose the concept of environmentally-appropriate technology for the rural context lacking economic resources and knowledge. Taking the case of a solar-powered cocoa dryer in Nias, Indonesia, this research employs a generic VDI 2222 engineering design and physiological modeling in conjunction with the conceptual understanding of environmental design and Design for the Environment (DfE) to demonstrate the proposed concept. The design considers locally available environment-friendly energy, materials, and signals to produce a well-functioning and affordable technology. Furthermore, this study involves field trials considering applicable cocoa quality standards in Indonesia (SNI 2323:2008) and market needs. The results show that the technology can include more than 95% of local materials and construction processes while using solar as a renewable energy source to generate the heat required by the cocoa drying process. More than 60% of the parts are degradable, while the rest are reusable. The technology also performs well technically, reaching the desired moisture content of the dried cocoa beans to meet market needs. These results demonstrate the possibility of an environmentally-appropriate technology, which is affordable, technically functioning, and environment-friendly for less resourceful regions such as rural areas. Future studies can use the approach to provide various technologies with similar techno-economic and environmental characteristics for different contexts lacking resources and knowledge.

1. Introduction

Climate change has significantly induced more vulnerabilities to vulnerable communities worldwide. Ofoegbu et al.’s review (2017) revealed the negative effect of climate change and its variability on vulnerable communities. Benevolenza and DeRigne (2019) suggested that climate change may further induce critical exposures to the most vulnerable subsets of the vulnerable communities. Gidley et al. (2009) even proposed the possibilities of “radical, rapid, and potentially irreversible changes” brought by climate change to various facets of socio-ecological systems at both local and global levels. Historically, climate change continuously records a new high of temperature worldwide, pushing the upper borderline of global temperature at a distressing pace. Arnell et al. (2019) estimated up to 5 °C potential temperature increase from pre-industrial baseline. Meanwhile, Yu and Ruggieri (2019) analyzed potentially remarkable shifts of interactions among climatic variables, including temperature, which could trigger severe impacts on numerous bio-physical systems. Moritz et al. (2002) observed that the climatic changes could deliver extensive impact on the critical pillars of global environmental stability, including the far-reaching role of the north pole. The consistent increases of temperature also affect various facets of human-environment systems, by which scientists acknowledge climate change as a carrying force of more negative consequences than positive ones despite the variety of occurrences. Svenning and Sandel (2013), for instance, studied the impact of climate changes on the changing vegetation in the near future. They discovered that climatic changes would disrupt the vegetation dynamics by inducing disequilibrium all over the ecosystems. Sisco et al. (2017),
on the other hand, reviewed numerous studies that found evidence of climate change-induced extreme weather events (EWEs). Stott (2016) notably revealed consistent evidence of human-induced EWE-causing climate changes, emphasizing the reciprocal influence of humans and the environment. Meanwhile, other research investigated the relationships between climate change and food security at either production (Campbell et al., 2016) or consumption sides (Wheeler and von Braun, 2013), threatening food availability at global and local levels. Then, Boholm and Prutzer (2017) investigated different scenarios of climate change that relate to the risk management of drinking water, while Delpía et al. (2009) focused on the impact of climate change on the quality of drinking water beyond typical availability issues and other hydrological risks. Looking at the explanations, the impacts of climate change appear more formidable over time, and result in multi-faceted influences. Those immediate consequences are making society more vulnerable than ever.

Remarkably, climate change delivers much stronger impacts to rural areas, which lack resources and knowledge inadequacy to stand against overwhelming consequences brought by climate changes. Locarelli et al. (2017) discovered little attention to overcoming climate change impacts in rural contexts through necessary means, including climate actions/policies. In fact, rural areas are considered vulnerable even without climate change due to their disadvantages in accessing economic resources and knowledge sources. Xenarios et al. (2019) suggested the inherent vulnerabilities of rural societies in less developed regions, including those classified as either developing or low-income economies. It makes them alarmingly vulnerable to the impact of climate change. Of the inherent vulnerabilities, they suggested a couple of fundamental factors that include geographical remoteness, physical and information accessibility, and low-performing infrastructure. Sianipar et al. (2014a) warned that the broad exposure due to the inherent vulnerabilities, which, as Xenarios et al. (2019) proposed, could be compounded by climate-induced exogenous factors, would imply a substantial chance for less developed regions to fall into multi-dimensional crisis. The economic disadvantages make them unable to establish a solid economic foundation for their development progress, resulting in fragile fundamental economics against both long-term and sudden impacts of climate change. Alam (2017) gave a notion about how the livelihood cycle of rural households would lead to their climate vulnerabilities. The climate vulnerabilities, as discussed by Benevolenza and DeRigne (2019), could also produce extended physical and mental impacts on disadvantaged subsets of the rural population. Sianipar et al. (2014a) mentioned that the fragile foundation of rural communities makes them critically vulnerable against exogenous forces, including slow-onset and/or rapid-onset climate-induced factors. On the other hand, the inaccessibility of knowledge sources becomes a compounded factor for their inability to mitigate climate risks. Mugambiwa (2018) suggested the critical role of indigenous knowledge systems for climate change adaptation in the rural context, while Nyahunda and Tirivangani (2019) emphasized that indigenous knowledge systems are unpredictable, leading to inadequate technical and scientific methods for the adaptation. Alam et al. (2017) discovered that knowledge-dependent perceptions of rural households on climate change affect their coping mechanisms. Kuruppu and Liverman (2011) found the direct influence of cognitive perception and culture on preparing the mentality of rural societies for climate adaptation. Then, Nielsen and Reenberg (2010) acknowledged the existence of cultural issues that lead to the success or failure of climate adaptation in rural areas.

To address climate change, scientists at least suggest three-side efforts. The first one addresses the impacts of climate change after they occur. Arnall (2019) gave an example of resettlement as an approach for climate change adaptation, while Hayes et al. (2018) presented suggestions to deal with mental health issues that emerge as the consequences of climatic change. The second side is by learning the causes of climate change and attempts to address the climate change before the cause occurs. Besides adaptation, Evans et al. (2014) acknowledged the necessity of mitigation, including how a solid focus on adaptation could trigger greater willingness to establish better climate mitigation. Østergaard and Lund (2010) emphasized the need for a more bottom-up community approach to establish climate change mitigation. Then, the third side is by detecting any ongoing accumulation of causes, which would eventually affect the climate and cause climatic changes in either near or distant future, and attempt to reduce the pace of accumulation. Campbell et al. (2016) presented a review of necessary efforts concerning food security issues. Then, Hansen et al. (2019) suggested a parallel focus on poverty alleviation in rural areas for better-managed climate risks. Together with these three-side efforts, scientists recognize the environment as a balancing force to climate change. Numerous efforts have emerged to take better care of the environment. Gidley et al. (2009) suggested a participatory approach for communities, while Häder and Barnes (2019) reviewed possibilities to maintain the linkages and reciprocal responses between natural ecosystems. Regrettably, human-induced exploitations over natural resources occur alongside inadequate efforts to maintain ecological balance. Lewis and Maslin (2015) proposed the diminishing effects of human-made activities over global environmental changes. Münster (2020) criticized the unilateral-instrumental concepts promoted by natural scientists that largely neglect the critical role of other disciplines, making it challenging for others to produce comprehensive efforts. Tamburino and Bravo (2021) promoted the idea of reconciliation between progressive ecological dynamics and anthropogenic development. In fact, the barriers and challenges have disrupted the capability of the environment to rebalance climate-affecting causes. Besides, some issues relevant to the barriers and challenges do not seem to reduce disconcerting human-induced disruptions over ecological balance. Wheeler and von Braun (2013) discovered biases in research that widen the gaps between good intentions and field evidence, leading to an imbalance of attention in the climate decision-making process. Barry (2012) went deeper to mention intangible factors such as political economy that deliver subtle yet decisive influence to human efforts towards greener civic activities.

Among numerous human-made efforts, new technological advances claim to contribute to the better care of the environment. Technologies suggest their environment-friendly characteristics in parallel to the three-side efforts. Some of them claim to stand against the consequences of climate change. As an example, Brown and Bauer (2016) reported the application of appropriate emergency technologies for natural disaster situations. Meanwhile, some others attempt to resolve accumulations of climate-affecting causes. For instance, Wibardjaka et al. (2019) attempted to address climate change through appropriate crop and soil management techniques for maintaining the soil fertility of rainfed rice plots at lowland altitudes. Then, the rests claim to produce more negligible environmental impacts. For example, Campbell et al. (2016) discussed literature on environmental-friendly technologies to support the risk reduction of food security against climate changes. Talai et al. (2014) referred to the roll-out of low carbon technologies to maintain the progressive development of energy-hungry sectors while also controlling, reducing, and/or preventing anthropogenic GHG emissions. Those technologies generally help make a better environment; however, their provisions typically occur at the expense of higher investments required. Hansen et al. (2019) mentioned an intense need to alleviate economic constraints relevant to savings, credit, and other liquidity issues for stimulating technology adoption practices in rural areas. Alam et al. (2017) suggested providing technological solutions that are fitted in specific rural contexts in conjunction with additional support from the government and Non-Governmental Organizations (NGOs). When there is a need to provide environment-friendly technologies for rural areas, inappropriate technological advances become impractical. The economic and knowledge constraints in rural areas have become critical challenges for rural stakeholders to get immersed in reducing climate risks by applying expensive environment-friendly technologies. Hansen et al. (2019) reviewed the possibilities of reducing climate risks for smallholder rural farmers by coupling technological introduction and
institutional options. While it is true that exogenous actors such as the government or climate-focused organizations may help rural areas to obtain technologies as such (Dietz et al., 2007), their dependencies to those actors bring higher risks when the external supports disappear somewhere in the future (Sianipar et al., 2013c). Besides, Nelson et al. (2010) warned that an imperfect examination of rural vulnerabilities by higher-level governments could make climate risks remain unresolved. The added risks then expose rural areas to a more significant possibility to fall into another crisis, making them more vulnerable than ever before (Zurovec et al., 2017).

Looking at all explanations above, there is a prevailing conflict of interests between the provision of highly efficient environment-friendly technologies and the scarce economic and knowledge resources in rural areas. Unfortunately, literature on the matters typically applied one perspective while neglecting the other. It implies that the focus of existing research has not holistically considered technological solutions and rural users at the same level in the provision of an environment-friendly technology that fits with its rural context, leaving the research gap for this research to address. Therefore, this study aims at discovering whether the provision of environment-friendly technologies would be possible under the lack of economic resources and knowledge available in rural areas. Theoretically, it is imperative to compare and contrast relevant topics and issues for exploring any potential concept to address the research gap. In practice, it is consequently critical to understand the provision at a practical level by demonstrating the concept in a case study. This research shall hence answer the following research questions:

Q1. How to approach the provision of environment-friendly technologies for rural areas, considering their lack of resources and knowledge?

Q2. How the approach applies to the practice of technological provision in rural areas?

Q3. How to ensure the environment-friendliness of the technology considering particularities of a rural area?

2. Literature review

2.1. Technology for rural climate actions

Against climate change, technology is an acknowledged force in the effort to prevent, reduce, or delay the causes of climate change. As noted by Talaei et al. (2014), technologies claiming to be climate-friendly should first be friendly to the surrounding environment. Besides, climate mitigation and adaptation technologies should deliver solid signs of progress to generate technological advances that would help against climate changes in the future. Shrivastava (2013) gave an example of modifying drivers’ behavior by applying laws prohibiting left turns. According to their analysis, left turns in regions with the right-side driving rule consume more energy. In aggregate, the elimination could help promote an effective driving distance, a shorter transportation time, reducing fuel consumption, and eventually reducing GHG emissions.

2.2. Technology in rural areas: Fitting to the context

In a rural context, the provision of environment-friendly technologies shall go through local barriers typically inherited from the lack of resources. The first barrier relates to technical knowledge available in rural areas. According to Mercer et al. (2007), indigenous knowledge has a distinguished merit in solving common problems throughout local history. However, it is particularly challenging to cope with technological issues against climate change, which, as Pin et al. (2021) stated, require exogenous knowledge rapidly developing outside the rural regions. In general, the absence of necessary knowledge makes it difficult for rural stakeholders to build, maintain, dispose of, or recycle technological solutions by themselves. Jaya (2006) mentioned that traditional knowledge might not be adequate to act consistently as the primary foundation of prevention efforts against environmental disasters and resource exploitation. Meanwhile, Gupta et al. (2003) promoted another organization actor (NGO) to help articulate socio-ethical capital in enhancing indigenous knowledge, values, and institutions to foster technological innovations at the grassroots level. At times, however, those efforts may make rural communities depend on the technical knowledge of their exogenous partners. Considering that the exogenous support may not last forever, it is practically difficult to maintain sus-tainable technological advancement. Green (1999) suggested a solid focus on cultural and organizational issues within the local social structure. In the process, technology development requires the involvement of multiple stakeholders to establish synergy among different interests. In addition, Sianipar et al. (2013c) advocated empowerment as the fundamental approach to induce internal pushes towards sustainable technological development.

Furthermore, the second barrier (i.e., economic) relates tightly to the first. Lacking economic resources has made rural stakeholders unable to acquire the required exogenous knowledge to enhance their indigenous expertise. Besides, the economic constraints prevent them from providing the best technologies available to gain maximum benefits. Hansen et al. (2019) concluded that socio-economic context is parallelly critical with bio-physical factors to deliver the maximum potential of technologies for climate risk reduction and resilience.
(2019) stated that, to ensure the availability and accessibility of technologies for mitigation and adaptation practices, rural communities primarily depend on initiatives driven by cross-national donors. Then, the third category of barriers includes long-practiced non-environment-friendly activities in rural areas. Gyampoh et al. (2009) identified the need to integrate indigenous knowledge and modern scientific progress to reshape existing coping mechanisms against climate change. In contrast, Nyahunda and Tirivangasi (2019) proposed technoscience adaptive methods to produce revised versions of exogenous technical solutions that would function effectively and efficiently given the local context. In the process, techno-economic barriers make rural stakeholders unable to stop, reduce, or reshape the practices without triggering additional problems (Hansen et al., 2019). Since the socio-economic conditions of rural households vary to a large degree (Alam, 2017), requiring rural stakeholders to provide technological solutions for those non-environment-friendly practices would practically be difficult considering the techno-economic barriers. The provision of environment-friendly technologies for rural areas under lack of resources and knowledge, therefore, requires an alternative understanding of how the provision shall take the techno-economic and environmental barriers into account.

2.3. Understanding technological appropriateness

Rather than treating technology as environment-friendly by claiming it to emit more negligible environmental impacts or to resolve existing environmental impacts (supply-driven), the provision shall use the understanding of technological appropriateness. Technological appropriateness refers to the characteristics of a technology that considers its target context as the sole basis of its design process in an understandable manner for its target users. Sharif and Sundararajan (1984) stated that technological appropriateness constitutes how a technology resonates with the techno-economic, environmental, sociocultural, and politico-legal qualities of the surroundings. Meanwhile, Sianipar et al. (2013a) distinguished the reciprocal influences between the technology and existing circumstances relevant to the context of its potential users. Bishop (2021) concluded the key role of local users in creating solutions according to their needs and desired benefits. When a technology targets a rural context alongside its lack of resources and knowledge, the design of the technology takes local techno-economic and environmental matters to establish the construct and characteristics of the technology. Wicklein (2013) suggested interpreting these matters into some practical issues according to local situations, including but not limited to systems independence, an image of modernity, cost of technology, risk factors, evolutionary capacity, and single-/multipurpose function(s). Besides, Sharif and Sundararajan (1984) suggested the derivations of techno-economic and environmental surroundings to establish the specific purpose and utilizations of technology. Technology becomes appropriate for the local context, indicating high technological appropriateness for the targeted rural areas. In that sense, the concept of technological appropriateness goes along with the concerns in providing environment-friendly technologies for rural areas.

In the scholarly discourse on appropriate technology, Pin et al. (2021) mentioned multiple tiers of appropriateness. Sianipar et al. (2013a) stated that the first (basic) level includes technical and economic appropriateness. In general, technical appropriateness occurs when a technology design can deliver a well-functioning technical artifact that would help rural stakeholders to conduct a targeted process faster and/or better. Haas et al. (2016) noted that, for technology to contribute to rural development, the technology design must first consider technical functions. Wihardjaka et al. (2019) suggested optimizing technical performance to deliver better productivity, eventually leading to economic benefits. Talaei et al. (2014) presented an example to discover technical competitiveness and impact of technology by applying Technology Needs Assessment in conjunction with SWOT analysis. Meanwhile, economic appropriateness emerges when the technology is at least affordable for rural stakeholders given the economic capabilities of its target users. Hoffmann et al. (2007) suggested that, whether it occurs through technology transfer, adaptation, or design, the introduction of technology should evaluate economic possibilities for potential users. Practically, the users can be local makers/manufacturers, buyers, and/or operators. Sianipar et al. (2013c) advocated that economic appropriateness is on par with technical appropriateness, by which they form the techno-economic/basic appropriateness of technology. Wicklein (2013) suggested the parallel considerations of cost and risk to avoid any disruption on technology lifecycle (making until disposal) in the future. Roughly speaking, affordability shall therefore prevent the provision of technology from disrupting the livelihoods of target users for a lengthened time or making them unable to fulfill their basic needs.

Furthermore, the second level of technology appropriateness relates to environmental aspects (Sianipar et al., 2013a). In general, it includes passive and active tactics. Passive tactics cover the optimum use of locally available materials to ensure fewer emissions from the transports of materials from other areas. Konstantinou and Prieto-Hoces (2018) stated that passive design principles for technological systems should see within the natural interactions of the technologies and surrounding systems. Practically, it implies preferences towards the optimization of existing resources rather than attempts to pull exogenous additions from beyond the surrounding systems. Meanwhile, Wakraha et al. (2010) concluded that local availability of materials and labor is critical in the provision of appropriate technologies for rural regions. Regarding waste issues, the material consideration should also focus on eco-friendly specifications and recycled items among locally available materials. An environmentally-appropriate technology, however, may still include materials from external sources. Still, the design process shall limit the inclusion to a bare minimum. On the other hand, active tactics include the ideas of durability, degradability, appropriate technology reusability, and emissions. Sianipar et al. (2014b) suggested that those ideas must be carefully crafted to make technological solutions “able, feasible, and visible” to improve rural actions. In general, an environmentally-appropriate technology shall be durable enough to use for a particular lifetime (López-González et al., 2018), have a consis-erate number of degradable components after the lifetime (Sandwell et al., 2016), have reusable parts for its non-degradable components (Sianipar et al., 2013b), and emit low emissions to the surrounding environment (Sahu et al., 2011).

Then, the third level is social appropriateness, which includes tangible and intangible social factors. Pin et al. (2021) found that, for a technology to fit with societal circumstances, the technology should deliver social impact, including but not limited to social license, community involvement, organizational norms, and aesthetics. Meanwhile, Sianipar et al. (2013a) suggested tangible and intangible factors that constitute how technology could be appropriate for its social context. On the one hand, tangible social factors (e.g., employment opportunities, daily routines) might be apparent during communications with local people, making them considerably straightforward to measure. On the other hand, intangible measures require a thoughtful approach to the target context of technology because they can include more cultural, judicial, normative, and political issues. Tharakan (2011) stated the central position of considering social justice and sustainability in the provision of appropriate technologies. In the process, it is imperative to acknowledge any diversity and differences that emerge in the interactions among local people or between exogenous-indigenous actors. Looking at these explanations, pursuing a socially appropriate technology is a highly challenging task in providing technology for rural settings. Bishop (2021), therefore, suggested an active dialogue between innovators and potential users regarding cultural norms and social values to gain correct perspectives over ethical design and potential impact in the future.
2.4. Research positioning: Environmentally-appropriate technology

Considering the close relation between techno-economic and environmental barriers, this study argues that the inclusion of techno-economic and environmental appropriateness is critical in the provision of environment-friendly technology for rural contexts. Conceptually, therefore, the design process would deliver an environmentally-appropriate technology, which, basically, is also technically and economically-appropriate (Pin et al., 2021). According to Sianipar et al. (2013a), the two-level appropriateness shall begin from concerns in a targeted context, include them throughout design stages, and end to solve the local concerns. To deliver an environmentally-appropriate technology, this study takes the conceptual understanding of environmental design and the practical approach of the Design for the Environment (DfE). For an environmentally-appropriate technology, energy use is critical since it is considered the largest source of inefficiency in a technology. Garniati et al. (2014) suggested that the accessibility of sustainable energy could deliver reciprocal influence with particular vulnerabilities of rural society. Vaccari et al. (2012) proposed a workaround for the accessibility issue by relying on technical improvements of locally available technologies to consume less energy. The conceptual understanding of environmental design suggests a three-way scheme to produce an environment-friendly product. The scheme begins with reducing energy demand, using sustainable-renewable energy sources, and using fossil energy, if necessary, as efficiently as possible. These three ways constitute global progress to use finite energy sources efficiently, eventually compensating them with as much as possible renewable energy over time (Entrop and Brouwers, 2010). In fact, the minimized use of energy is parallel to some concerns promoted by DfE, which center on improving energy efficiency for any technology with dominant energy-consuming operations during its lifetime (Birch et al., 2012).

Besides, DfE suggests additional focuses on materials and signals. In terms of materials, DfE considers waste generation as the basis for designing an environment-friendly technology. The focus on waste generation centers on the minimization of waste and harmful materials, which implies the inclusion of recyclability, reusability, and modularity. Birch et al. (2012) suggested avoiding production waste by optimizing packaging-related processes and materials. Meanwhile, Hauschild et al. (2004) proposed parallel focuses on the extension of technology lifetime, the use of eco-friendly materials for the technology, and the disposal approach at the end of the lifetime. These concepts are parallel to the concept of environmental appropriateness, making them helpful to consider in this study. In terms of signals, DfE suggests product lifetime to lay the foundation of environmental appropriateness. The product lifetime relates to the simplified/optimized organization of functional units in technology and its lengthened lifetime. Bovea and Pérez-Belis (2012) suggested considering an issue as such from the beginning of the design process, balancing environmental impact with techno-economic performance. Birch et al. (2012) stated that the consideration should systematically consider end-to-end technology lifetime from design to recycling. Besides, the design and development processes should consider the initial lifetime as an integral part of the environmental performance beyond technical specifications. That way, engineering design is becoming critical in ensuring the environmental appropriateness of technology design, use, maintenance, and disposal.

This study establishes the research framework based on the positioning of included concepts and theories (Fig. 1). Solid lines indicate direct involvement, while dashed lines are information flows. First, the input and outputs (I/O) are energy, materials, and signals, forming a typical design black box. This study uses the understanding of environmental design and DfE to discover these I/Os. Besides, this research puts the technology within the design process, by which the design process shall consider locally available and environment-friendly energy, materials, and signals. Second, this study applies a bottom-up perspective by treating rural stakeholders as the subject of development, meaning that they are the driving force of technology design and not only treated as neglected users/objects of development. Consequently, the design process shall involve them in each design stage. Every activity in the design process thus includes efforts to listen to, work with, and deliver the technology for rural stakeholders. In practice, the technology design includes their concerns as the basis for techno-economic and environmental appropriateness of the technology.

To ensure the active involvement of rural stakeholders, the designer/engineer takes a step back to a more assisting/guiding position. In that sense, the tasks include assisting the stakeholders and guiding the design process rather than making one-sided design decisions.

3. Methodology

3.1. Research design

This study attempts to design an environmentally-appropriate technology for a rural context that considers the lack of resources and knowledge of its targeted users. Selecting the basis of the design method shall thus reflect particularities of the constrained circumstances of rural areas as the subject of development in this research work. Basically, the practical reason for a cautious concern as such is to ensure an inclusive consideration of techno-economic and environmental barriers encountered in the fields. Besides, the nature of technology design in this study requires flexibility to cover potential alterations during design processes, by which a much simpler set of design guidelines would be much more advantageous. To deliver the environmentally-appropriate technology, therefore, this study requires a design method that may bridge scientific and creative processes in a flexible sequence of design activities. As the basis of the design process, this research takes the 4-stage generic design method of VDI-2222 (Kurniawati and Dzikraa, 2018; Wiendahl, 1981), which is a simplified version of its 7-stage standard. This research selects the simplified version by considering its capability in establishing an advanced design process with less complexity and more flexibility. In general, the 4-stage design process includes Analyzing, Concepting, Designing, and Finalizing.

Furthermore, the research framework (Fig. 1), along with the second (Q2) and third research questions (Q3), urges a stronger focus on the involvement of rural stakeholders throughout design stages. Besides, it demands the inclusion of stakeholder-driven assessments on techno-economic and environmental appropriateness. Thus, this study modifies the 4-stage basis into a 5-stage formal design process (Fig. 2). The
first stage is the Preliminary Study, which relates to the Analyzing. This stage focuses on discovering the two-level appropriateness in the form of desired requirements by rural stakeholders. The second stage is Conceptual Design, which is similar to the Concepting stage. This stage intentionally applies physiological modeling (Sianipar et al., 2014c) rather than typical functional modeling since it allows a more straightforward logical interpretation from idea to process then functions. The intention is to deliver a more understandable conceptual design process for rural stakeholders without the necessary technical knowledge, which is desirable to ensure technical appropriateness (Pin et al., 2021; Sianipar et al., 2014a). The third stage is Design Embodiment, which translates to the Designing stage. In this stage, the physiological concept is transformed into a detailed design to be then constructed into a physical artifact. The fourth and fifth stages split the Finalizing stage into Field Trials and Economic-Environmental Assessment stages. The fourth stage constitutes an assessment of the technical performance of the technology, while the fifth stage focuses on assessing its economic and environmental performances. This study argues that field trials are more understandable to rural stakeholders than numerical scientific calculations and/or laboratory experiments. Besides, field trials allow a direct involvement of rural stakeholders in the technical assessment process. Then, a separate economic and environmental assessment in the fifth stage allows a more focused process by involving discussions with rural stakeholders to judge the economic and environmental appropriateness.

3.2. Case study

Cocoa (Theobroma cacao L.) is one of the most consumed perennial crops globally (Gilbert, 2016; Moser et al., 2010). Most cocoa production capacity occurs in African countries such as Ivory Coast, Ghana, and Cameroon. It has triggered most cocoa-related research to focus on cocoa production activities in the continent. Meanwhile, Asian countries have seen more dynamic fluctuations of cocoa production capacities, witnessing the fall of Malaysia from the world’s third-biggest cocoa producer and the rise of Indonesia to reach as high as the third position (Effendy et al., 2019; Moser et al., 2010). Despite producing the second-largest cocoa production capacity at a continental level after Africa, the fluctuation indicates a more fragile foundation of the cocoa industry in the Asian continent, requiring more research on cocoa production issues in Asian countries to ensure a sustainable cocoa industry in the continent. In Asia, Indonesia’s cocoa production capacity has held the continent’s top position for a long time (Moser et al., 2010; Witjaksono, 2016). In Indonesia, smallholder farmers share the majority of cocoa production capacity, while virtually all cocoa production activities occur in rural areas (Effendy et al., 2019; Pomp and Burger, 1995). These facts, however, have made the cocoa industry in Indonesia extremely vulnerable. The government and local organizations have been attempting to address the vulnerability, yet those efforts primarily focus on major regions with solid backing from state-owned plantations and private estates. Lesser considered regions, including Nias in North Sumatra (Fig. 3), remain vulnerable despite their more substantial dependencies to smallholder rural farmers than the major cocoa-producing regions.

Apart from the remote location of Nias on the edge of the Indian Ocean, smallholder cocoa farmers in Nias have been dealing with difficulties to improve the quality of their traded product (dried cocoa beans) due to their lack of economic resources and available knowledge. It has made them greatly dependent on intermediaries for reprocessing traded cocoa beans to reach the minimum quality level demanded by the market. The reprocessing typically includes a drying process, which smallholder rural farmers in Nias cannot conduct properly. Due to the high volume of cocoa beans to reprocess from numerous smallholder farmers for each intermediary actor, the drying process conducted by intermediaries typically involves dryers with GHG-emitting fuels such as biomass-powered convection dryers or LNG-fueled ovens. Dryers as such thus require high investments, which typical smallholder farmers are not capable of fulfilling. Besides, these dryers produce high GHG emissions. Therefore, there is an opportunity to reduce the dependencies of smallholder cocoa farmers to intermediaries by providing a well-functioning cocoa dryer. Considering the highly GHG-emitting cocoa dryers of intermediaries, providing cocoa dryers for smallholder farmers can also promote a more environmentally-appropriate version of the technology. The remoteness of Nias also implies the necessity of locally available materials, which would be an opening gate to promote a technically appropriate design. Then, the technology shall consider the economic and knowledge constraints of rural cocoa farmers in Nias, implying a requirement for an affordable, technically functioning, and environment-friendly cocoa dryer. Based on the compounded factors above, this study takes the provisioning of an environmentally-appropriate cocoa drying technology for smallholder rural farmers in Nias, Indonesia, as the case study to answer the second research question.

3.3. Trial protocol

The design of field trials considers several quality parameters covering both standardized and desired performances of the technology being designed (cocoa dryer) in bringing the product it delivers (dried cocoa beans) that meets market demands. Therefore, testing parameters for data retrieval and observations focus on the drying-related quality of cocoa beans (Guehi et al., 2010; Mishra et al., 2020; Nukulwar and Tungikar, 2021). In terms of the end-product quality (dried cocoa...
beans), this study considers size-weight classification and moisture content as the measures. For size and weight, this study applies the Indonesian National Standard (Standard Nasional Indonesia – SNI) no. 2323:2008 that revises prior applicable standard (01-2323-2002) (NSAI, 2008; Sulistyowati et al., 2005). The standard suggests five classifications of the size and weight of dried beans per 100 g sample (Table 1). As for moisture content, the typical consensus is to achieve the maximum moisture content at 7.5% of dry cocoa beans with a 7%–7.5% normal range (Hii et al., 2008; Tardzenyuy et al., 2020). However, this study considers locally applicable standards to ensure the acceptance of the resulting product in the market. A preliminary study shall reveal the local standard as a desirable requirement. In terms of the quality of the process served by the technology (drying process), this study includes temperature, humidity, and drying speed as the measures. This study measures the temperature inside the dryer (drying temperature) and outside the dryer (outdoor as control temperature). Parallel to moisture content as a measure of the product processed (cocoa beans), the trial takes outside (outdoor) humidity into account. In terms of drying speed, this study considers the desired range of the required drying period. The preliminary study shall then include an inquiry into the desired drying speed by immediate technology users (local farmers).

Furthermore, the field trials apply a testing protocol that covers these standardized and desired measures in an orderly manner. As the baseline, there are three basic rules for the trials. The first rule is the replication of testing, with which the field trials apply four test replications for the technology (cocoa dryer) to establish a pattern of behavior. The second rule is the total weight of wet cocoa beans for each replication. The weight per replication follows the desired specification of the technology, which appears during the preliminary study. In other words, the total weight for the field trials is four times the weight per replication. Then, the third rule is the signal that each replication shall refer to for ending the observed process (beans drying). In this study, the signal follows the targeted moisture content of the dried cocoa beans. When cocoa beans being dried reach the moisture level, it signals the replication (one drying process) to stop. Furthermore, the flow of one replication consists of four general stages. To ensure proper diffusion of

| Category | Sample | Range [gram] | Range [# of dry beans] |
|----------|--------|--------------|------------------------|
| AA       | 100    | ≤ 85         |                        |
| A        | 100    | 86–100       |                        |
| B        | 100    | 101–110      |                        |
| C        | 100    | 111–120      |                        |
| S        | 100    | > 120        |                        |

**Table 1**
Size-weight classification of dried cocoa beans according to SNI 2323:2008.
the environmentally-appropriate technology into existing daily routines, the trial/testing protocol suggests a testing flow that follows typical drying activities currently conducted by local cocoa farmers. The protocol involves a pair of local cocoa farmers as testers. First, testers spread wet cocoa beans manually throughout the drying space with an equal thickness. At designated hours, the testers measure and note the moisture, weight, and temperature of the beans. Besides, the testers measure the outside temperature as well as air humidity. Equipment for the measurements includes a digital grain moisture tester (moisture), digital thermometer gun and digital wired thermometer (temperature), and humidity meter (humidity). Third, the drying ends when the stop signal (moisture content) reaches the desired range. If the stop signal has not been reached after the last measurement for the day, testers take the wet beans into a storage room to have another drying day in the following daytime. The testers shall use plastic sacks to store the beans and tie them tight to prevent the re-absorption of room humidity. After the stop signal (moisture level) informs the replication to finish, the testers take all dried beans out from the drying space to count the number of dry cocoa beans per 100 g weight.

4. Results

4.1. Preliminary study: Desired requirements

Desired requirements for an appropriate solution shall come from the perspective of relevant stakeholders within the targeted societal entity or the region the entity is living in (Shoultz et al., 2006). There are at least three stakeholders in regional development, including those in rural areas. The three-party stakeholders are the community, experts, and the government (Chiang et al., 2021; Hani et al., 2013). This study involves several interviewees for each group of stakeholders to gather a complete sense of what the stakeholders desire towards the provision of new technology (cocoa dryer) for its target users (smallholder cocoa farmers in Nias, Indonesia). Table 2 provides the number of discussants/interviewees involved in each design stage. In this study, the community members refer to the smallholder cocoa farmers in Nias. They are the target users; therefore, their involvement in the design stages is essential to allow us to listen to their concerns and ideas (Fressoli et al., 2014; Goodier, 2013; Pin et al., 2021), which would act as inputs for establishing basic requirements for the new dryer. Meanwhile, the experts involve those (local and external) with expertise in cocoa postharvest processing, local economic development, and environmental design. Their voices are critical since they have established scientific expertise in their respective specializations, which would be the basis for developing extended requirements for the designed technology. Local experts are essential in understanding locally available energy source(s), raw materials, and construction processes. In parallel, external experts are the complementary sources of relevant information and the triangulators of field data gathered from local stakeholders. Then, the government involves local administrations in the target rural area, who, in this case, are the governments of North Sumatra and regencies in Nias island. The involvement of governmental actors would provide information on the market needs since they routinely monitor and regulate the supply and value chains. Besides, they can see from a

| Stakeholders                  | Design Stage | Discussants/interviewees |
|------------------------------|--------------|--------------------------|
| Community members            | X            | 14                       |
| Experts                      | X X X X X    | 4                        |
| Government officials         | X            | 6                        |

* I → Preliminary; II → Concepting; III → Embodiment; IV → Trials; V → Economic/Environmental Assessment.

Table 3 Desired requirements according to stakeholders.

| Item                   | ID | Qualification |
|------------------------|----|---------------|
| Technical Requirements  |   |               |
| Drying area            | T_R1| 2 × 1 [m]    |
| Drying rate            | T_R2| 10 [kg/m²]   |
| Drying temperature     | T_R3| ≥ 50 [°C]    |
| Drying time            | T_R4| ≤ 3 [days]; faster is better |
| Energy source          | T_R5| Solar (sunlight) |
| Moisture content       | T_R6| 7.5% ± 0.5   |
| Economic Requirements   |   |               |
| Material costs         | E_R1| ≤ IDR 2,000,000 |
| Worker costs           | E_R2| ≤ IDR 500,000  |
| Environmental Requirements | |               |
| Raw materials          | V_R1| 1st priority → wood |
| Degradable parts       | V_R2| 2nd priority → zinc plate |
| Reusable parts         | V_R3| ≥ 50%         |
| Durability             | V_R4| ≥ 3 [years]   |

* T_R → Technical Requirement X; E_RX → Economic Requirement X; V_RX → Environmental Requirement X.
of four environmental requirements. Community members state their preference to use wood as the primary choice for raw materials, while local experts suggest zinc plate as an alternative material since it is commonly available in the area. Wood is a degradable material, which supports the primary objective of this study: providing environmentally-appropriate technology. Interestingly, local experts suggest zinc plate even though it is a non-degradable material. Including zinc as the second priority material maintains wood as the primary choice of materials. For the number of degradable parts, local and external experts suggest that at least half of the components should be degradable, while the rest or more should be reusable. Degradability and reusability would be critical to ensure minimum environmental impacts from the parts included in the drying technology. Then, community members suggest that the technology be useable for at least three years. Government officials confirm this to prevent undesirable investments from being repeated within a narrow time frame if the technology has a short lifetime.

4.2. Conceptual design: Physiological concept

In this stage, desired technical, economic, and environmental requirements for the cocoa dryer (Table 3) become the basis for constructing its physiological concept. This stage involves local and external experts to help interpret these requirements into precise physiological functions of the cocoa drying technology for the third design stage (Design Embodiment). First, the physiological idea (PI) establishes three pairs of I/O entities flanking the black box of the dryer (Fig. 4). “Energy” is the first I/O entity, with solar/sunlight as the input and heat as the output. The second entity is “Object,” which is parallel to “Material” in typical design constructs. The object on the input side is wet cocoa beans with 10 kg/m² density, while on the output side is dry cocoa beans. The third I/O entity (Indicator) is parallel to “Signal” in common design thinking. Both input and output sides use moisture content as the indicator, from about 60% to 7.5% ± 0.5 as the desired final moisture level. The by-product of those three pairs of inputs and outputs is vaporized vapor, which disappears during the drying process. Water vapor fills the gap between input and output, completing the I/O balance.

Next, the conceptual modeling proceeds to several levels of interpretation in the form of physiological processes (PP) and functions (PF) (Fig. 4). First, the black box defines two basic processes (air heating and beans drying). Next, they form the Start Process (SP), Core Process (CP), and End Process (EP) as the working processes of the dryer. The logical flow begins with air heating, which connects normal air to the heating chamber. The incoming air is at outside temperature; thus, the heating chamber will collect solar light, generate heat, and produce heated air. This step constitutes the Start Process (SP). As for the beans drying, it consists of two sub-levels. The upper sub-level begins with heated air flowing from the heating chamber into the drying chamber. The heated air flows to dry wet cocoa beans in the drying chamber. The lower sub-level contains one process only, which traps some of the heated air from the heating chamber to prevent sudden temperature drops in the drying chamber due to occasionally disappearing solar lights. It is a logical and compact solution to maintain the temperature inside the drying chamber under changing solar radiation over time. The upper and lower sub-levels form the Core Processes (CPs). Then, the heated air exits the drying chamber by bringing vaporized water out. It acts as the End Process (EP).

For the subsequent physiological interpretation, the start (SP), core (CP), and end processes (EP) form four physiological processes (PPs) that constitute a fully functioning construct of the dryer. This study interprets SP as air heating chamber (PP1), CPs into drying chamber (PP2) and heat storage (PP3), and EP turns into air exhaust (PP4). These physiological processes transform into four physiological functions (PFs). The air heating chamber (PP1) becomes the air heater sub-assembly (PF1). The drying chamber (PP2) takes the form of a drying mat (PF1). The heat storage (PP3) forms the heat keeper (PF3). Then, the air exhaust (PP4) becomes the air exhaust function (PF4).

Fig. 4. Physiological modeling.
4.3. Design embodiment: From model to construction

In the third design stage, the physiological concept of the cocoa dryer (Fig. 4) becomes the foundation of logic for the design embodiment. This stage involves external experts to justify the fundamental logic and community members to construct the dryer physically. In general, physiological processes (PP) and functions (PFs) form the model of fully functioning drying mechanisms. First, a user (farmer) spreads wet cocoa beans on the drying mat (PF2) inside the drying chamber (PP2). In parallel, normal air enters the air heating chamber (PP1). The air heater (PF1) collects solar lights and generates heat to increase the temperature of normal/incoming air. After that, the heated air enters the drying chamber (PP2) to reduce the moisture level of the wet cocoa beans, which have been spread on the mat (PF2), by vaporizing their water content. The heat keeper (PF3) traps some heated dry air to regulate the temperature inside the drying chamber (PP2). The heated and humid air then exits the drying chamber (PP2) through air exhaust (PP4/PF4) to the outside environment. Furthermore, an external expert helps transform the operational flow into the embodiment design of the dryer (Fig. 5a). After discussions, the drying mat (PF2) uses a flat zinc plate to form the operational flow into the embodiment design of the dryer. The air heater (PF1) uses corrugated zinc plates to generate optimum heat since corrugated plates have a wider surface area than flat plates due to their 3-dimensional corrugates. The wider surface area gathers more sunlight, generating more heat from the same 2-dimensional area as flat plates. Design for the air heater takes a widened form on two sides of the drying chamber (PP2) to flow a high volume of heated air and prevent blank heating spots on the drying mat (PF2). Below the drying mat (PF2), the heat keeper (PF3) traps some of the heated air using an empty, isolated chamber without any air exhaust on its walls. Then, air exhaust (PP4/PF4) uses a small canopy added on top of the drying chamber (PP2) to allow the outflow of humid and heated air while also preventing any foreign objects (e.g., pebbles, heavy specks of dust, rainwater) from entering the drying chamber (PP2). In terms of materials, almost all the components of the dryers use wooden materials. Exceptions only apply to the drying mat (flat zinc plate), solar light collector/heat generator in the air heater (PF1), and some transparent covers for the air heating chamber (PF1) and drying chamber (PF2). During this stage, the use of covers comes up from local experts since the chambers require transparent covers to allow sunlight to pass through, but prevent undesirable exits of heated air. The covers use UV plastic that is locally available and typically applies to greenhouses.

4.4. Technical assessment: Field trials

This stage involves community members as testers of the dryer prototypes and local experts to guide the testing protocol and ensure correct implementation of the testing. Field trials begin with some arrangements of the testing schedule (Table 4). The schedule divides one daytime into four routines and one additional activity for the last drying day. At 9 a.m., testers put and spread wet cocoa beans on the drying mat. Measurements at this time include temperature (drying chamber, beans, and outside/outdoor) and outside humidity. At noon and 2 p.m., testers repeat these measurements without taking the beans out of the dryer. At 4 p.m., testers conduct the exact measurements; however, they should first take the beans out of the dryer. Testers then measure the moisture content of the beans. If it has not reached the desired moisture level (7.5% ± 0.5), testers keep the beans in their indoor storage for another drying day. When the measured moisture has reached the desired level, it signals the drying process to stop. On the last drying day (around 6 p.m.), testers bring and sell the dried beans to an immediate buyer. The buyer conducts the counting of beans and repeats the measurement of moisture content. All measurement techniques follow the SNI 2323:2008 standards. At each measurement time, testers note the weather as control information. Testers repeat the entire drying process and measurements four times to gather the pattern of drying behavior of the dryer. Table 4 provides the averaged results of four testing replications. The dryer appears to produce an average temperature of 52.9 °C (9 a.m.), 57.9 °C (noon), 60.3 °C (2 p.m.), and 56.8 °C (4 p.m.). With a daily average of drying temperature at 57.0 °C, a daily average of outside temperature at 35.6 °C, and a daily average of relative outside humidity at 61%, the dryer is able to produce a 2-day drying rate for sunny-dominated drying days, and a three-day rate for cloudy- or gloomy-dominated drying days. In other words, the fastest drying rate (two days) is the optimistic scenario, while the slowest (three days) acts as the pessimistic scenario.

4.5. Economic and environmental assessment

The fifth design stage assesses the economic and environmental performance of the designed and tested dryer (Fig. 5; Table 4) by considering the desired requirements in these two categories (Table 3). The assessment involves all stakeholders to determine whether the dryer meets each requirement. In terms of economic performance, the designed and tested dryer appears to meet both economic requirements since it is cost-effective and environmentally friendly. Table 4 Measurement schedule and averaged results from 4 replications.

| Time   | Humidity | Temperature [°C] |
|--------|----------|------------------|
|        | Inlet    | Outlet | Outside | Inside |
| 09:00  | 56%      | 67%    | 33.8    | 52.9   |
| 12:00  | 53%      | 63%    | 36.3    | 57.9   |
| 14:00  | 51%      | 57%    | 36.7    | 60.3   |
| 16:00  | 49%      | 58%    | 35.6    | 56.8   |
| Average| 52%      | 61%    | 35.6    | 57.0   |

Rate 2 days [sunny]; 3 days [cloudy/gloomy]
Table 5  
Economic and environmental performances.

| Economic Requirements | Desired Qualification | Result |
|------------------------|-----------------------|--------|
| Material cost          | E.R1  ≤ IDR 2,000,000 | IDR 1,007,375 |
| Worker cost            | E.R2 ≤ IDR 500,000    | IDR 360,000 |

| Environmental Requirements | V.R. |
|-----------------------------|------|
| Raw materials               | V.R1 1st priority → wood |
|                             | 2nd priority → zinc plate |
| Degradable parts            | V.R2 ≥ 50% |
| Reusable parts              | V.R3 ≥ all non-degradable parts |
| Durability                  | V.R4 ≥ 3 [years] |

*E.RX → Economic Requirement X; V.RX → Environmental Requirement X.

(Table 5). Material cost (E.R1) is the total cost of materials used during the construction process. After the calculation by community members, local experts, and government officials, the material cost of the dryer is IDR 1,007,375, sitting comfortably below the desired qualification at IDR 2,000,000. Regarding the worker cost (E.R2), the construction of the dryer requires three working days. It involves one experienced worker and an assistant. The experienced worker has an hourly wage of IDR 50,000, while the assistant receives IDR 50,000 daily. Therefore, community members state that a 3-day work involving these two workers would require a total of IDR 360,000 worker costs. It also sits at a comfortable distance from the desired maximum worker cost (IDR 500,000). In terms of environmental performance, the technically tested dryer appears to perform well beyond the desired qualifications (Table 5). In general, all components of the dryer are wooden parts, except the drying mat (flat zinc plate), air heater/heat collector (corrugated zinc plate), and transparent covers (UV plastic). In that sense, external experts state that the dryer meets the environmental requirement for raw materials (V.R1). Furthermore, the external experts also judge that the use of wooden parts has made about two-thirds of the dryer degradable. Besides, all non-degradable parts of the dryer are reusable. Thus, the external experts declare that the dryer fulfills the second environmental requirement (V.R2) with a comfortable margin. It also fulfills the third environmental requirement (V.R3) precisely at the minimum state of the desired qualification. Then, community members and external experts predict a three-year lifetime of the dryer. It refers to the maximum period of use until the degradable components of the dryer must be disposed of while the rest is still reusable. In other words, the dryer meets the last environmental requirement (V.R4) just at the minimum qualification.

5. Discussion

This study has attempted to address the gap in the provision of environmentally-appropriate technology under the lack of economic resources and the limited knowledge available. Taking the case of a solar-powered cocoa dryer for rural Nias, Indonesia, this study demonstrates the provision of an environmentally-appropriate technology (cocoa dryer) that is properly functioning and affordable for its users (smallholder cocoa farmers in Nias). Despite being the Asia’s largest cocoa-producing country, Indonesia possesses a cocoa industry that has long been dominated by smallholder farmers from decades ago (Pomp and Burger, 1995). However, these smallholder cocoa farmers have not had the opportunity to gain the most benefits within the cocoa supply chain. In this study, the failure occurs mainly due to farmers’ inability to deliver cocoa beans that meet market needs, especially with regard to the demand for moisture content. It confirms a recent finding by Effendy et al. (2019), who discovered the inefficient operations of smallholder farmers. In practice, it makes those farmers require external actors to help them reduce the gap of operational inefficiency. The situation triggers the involvement of intermediaries to reprocess the incoming cocoa beans from the farmers so that the dried beans would meet the quality level in the market. As in other similar situations, unfortunately, the extensive involvement of intermediaries in postharvest processing activities in Nias has significantly reduced the economic advantages of smallholder farmers over their product (dried cocoa beans). At times, there were efforts to introduce various incentives. Franzen and Mulder (2007) suggested that incentives through price premiums may motivate farmers to produce high-quality cocoa beans. However, similar to Pomp and Burger’s finding (1995), farmers in Nias tend to wait for their fellow farmers to begin capturing opportunities as such. Meanwhile, intermediaries do not waste their time to gain economic benefits from price premiums. In the end, farmers are constantly unable to gain the most benefits from their own products.

Unfortunately, bulk artificial redrying by intermediaries produces high environmental impacts. In fact, scholars have also observed similarly undesirable impacts from other intermediaries-operated reprocessing activities in various agricultural supply chains. Kaveh et al. (2021) have attempted to evaluate the GHG emissions of different drying methods, with P. atlantica (Persian turpentine tree) as the drying object. They found experimental evidence of high GHG emissions produced by artificial drying methods. It is parallel to the energy consumption of artificial dryers, which still use natural gas, gasoil, and/or heavy oil to run their steam, gas, or combined mechanisms. In terms of energy parameters, Motevali et al. (2014) experimented with the energy and thermal outputs of various drying methods. Focusing on chamomile, their research revealed different behavior between artificial dryers. Of these, microwave-related dryers have the highest energy output, yet they generally perform a decrease in efficiency in parallel to increasing microwave power. In contrast, vacuum dryers produce the minimum thermal and lowest energy outputs. Meanwhile, Kaveh et al. (2020) attempted to search for optimized settings for energy, drying, and thermal efficiencies. In several combinations, the research applied different settings for various drying mechanisms (convective, infrared, microwave, vacuum, and rotary dryer). Their results showed increasing trends in these efficiency parameters alongside elevated temperature and infrared/microwave power. This study found that the situation in Nias is consistent with the literature. In general, intermediaries operate artificial dryers that utilize a quasi-roast process or blower mechanism. The currently-operating dryers utilize fossil fuels such as gasoline or liquified natural gas (LNG) to produce the required heat, resulting in high GHG emissions. Consequently, the added processing by intermediaries further adds GHG emissions into the supply-chain downstream of Nias cocoa beans. In the end, it weakens the competitiveness of the cocoa supply chain in Nias, including cocoa beans as the main product, considering the increasing concern about environmental issues from the market.

Looking at the disadvantages of intermediary-operated drying, the straightforward solution is to ensure that farmers can finish the entire drying process. It intends to reduce the need for an additional drying process after the cocoa beans leave the producers’ hands, making the entire drying phase a farmers-operated postharvest processing process. In agreement with the work of Kitinoja et al. (2011), however, the introduction of well-improved postharvest technologies in Nias has its particular challenges. To return the drying process to smallholder farmers in Nias, they need a cocoa dryer that can adequately dry wet cocoa beans, is affordable, and fits the environmental context. Technically, a specific range of moisture level (7.5% ± 0.5) is the primary target of the dryer, which, as Fagunwa et al. (2009) found, is critical for preventing decayed beans, slowing mold growth, and decelerating reabsorption of moisture. In fact, dryers operated by intermediaries are also expensive, making it difficult for farmers to acquire technology as
such without disrupting their economic situation. It is parallel to the work of Lamidi et al. (2019), who suggested affordability as a critical factor to ensure a sustainable drying system for rural farmers. Considering the high environmental impacts of dryers owned by intermediaries, it discourages the suggestion for farmers to operate similar dryers. This study thus avoids the environmental concern when delivering the postharvest technological solution for smallholder cocoa farmers in Nias. The three-way concerns are typical situations in post-harvest processing conducted in rural areas, which, as stated by Sianipar et al. (2017), generate technical, economic, and environmental transformations. In general, emerging challenges addressed by a provided technology trigger corresponding transformations during the process. It goes along with the work of Pin et al. (2021), in which the input-output pairs imply the technical, economic, and environmental appropriateness of the technology to its rural context. This study, therefore, focuses on the three classes of appropriateness in providing a contextual technological solution for a farmers-operated drying process.

This research applies a 5-stage design process to deliver an environmentally-appropriate cocoa drying technology for smallholder farmers in Nias, Indonesia. This study argues for the participation of rural stakeholders in all design stages. In this work, the rural stakeholders are community members, local/external experts, and government officials. In the first stage (Preliminary Study), all stakeholders join in expressing their concerns, ideas, and suggestions regarding their desired requirements for the technology. It underlines the importance of listening to users and other rural stakeholders, supporting existing studies. Fressoli et al. (2014) stated that participatory approaches are necessary and critical to ensure distributed economic benefits and strong cooperation. Additionally, Haas et al. (2016) suggested that co-innovation between rural stakeholders and external knowledge providers requires active identification, understanding, sharing, and platform-building processes. These four processes are critical to enabling community-driven co-creation that can stimulate creative solutions. In terms of approach, Sperling et al. (2005) criticized typical one-sided development in the provision of technologies for rural areas. They urged external actors to reconsider their tactics to stimulate the growth of rural economic development by balancing the quality and affordability of technologies through interactions with internal actors. In that sense, the external–internal interactions imply that technological requirements, including environmental requirements, are not given. Instead, those requirements are unique for each case, suggesting that, in agreement with similar research, a bottom-up preliminary study is more appropriate. Heston and Pascawati (2021) pointed out a user-centered and benefit-driven problem statement as an essential quality of technology design. Meanwhile, Fatimah et al. (2020) stressed the “appropriateness” issue in a given development context to discover multidimensional requirements. Then, Pin et al. (2021) emphasized that technological requirements should emerge from an extended group of stakeholders, covering those with relevant interests and/or expertise to the target activity. In this study, these requirements appear in the form of local availability, degradability, and reusability as the basis for environmental appropriateness.

In the second stage (Conceptual Design), local and external experts take the lead to establish the physiological concept of the dryer. Sianipar et al. (2014c) argued that physiological modeling is more understandable, since it allows a step-by-step interpretation of technical functions based on visible processes currently undergoing. This study proves it by proposing a conceptual modeling process that allows rural stakeholders with inadequate scientific knowledge to understand how the conceptualization works. Taking the pairing of energy, material, and signal inputs with energy, material, and signal outputs through derivative modeling levels helps them maintain the feasibility of their entire design concept. On the one hand, it helps stakeholders translate the targeted process they have been routinely doing into the concept of an environmentally-appropriate design that would work well. On the other hand, a user-centered conceptual design process, to some extent, induces a sense of ownership towards the technology being designed since it emerges from visible processes they have been doing day-to-day. The two-sided advantages correspond to similar approaches suggested by previous studies. Tarazona-Romero et al. (2022) suggested that there should be a decentralized process over design decisions that cover energy, environment, and other technical issues. Hoffmann et al. (2007) emphasized that farmers regularly attempt to improve their agricultural activities, making it essential for researchers (designers) to let them express their ideas over their routine processes. In a widely-known term, it is critical to produce technology with social license, implying that the technology would by design be accepted and ready for a seamless application by its target users. It reinforces similar ideas presented in other studies. Zissman et al. (2014) applied a collaborative assessment process involving local stakeholders to produce acceptable and actionable decisions. Meanwhile, Nilsson et al. (2014) proposed linking technology design to the demands of immediate users for a sustained partnership between relevant stakeholders and foreign partners.

In the third stage (Design Embodiment), external experts join the stage to develop the detail design, while community members (smallholder farmers) join to construct a physical artifact from the detail design. At this stage, the embodiment process requires the scientific knowledge of external experts to ensure that the detailed design adequately follows the principles of good design. As with community members, this stage considers their expertise in constructing an artifact using locally available materials. It ensures that the detailed design is possible to construct by community members even if experts do not help them again in the future. Their combination suggests a balanced involvement of experts and non-experts as desired in typical inclusive developments. Gupta et al. (2015) suggested that a relational perspective (Greene, 2001) between stakeholders is critical in establishing an inclusive development. Particularly for technology design, Pin et al. (2021) emphasized the strategic importance of reciprocal communications between “foreign” and “local” experts to translate design decisions into physical construction. Meanwhile, Pouw and Gupta (2017) argued that inclusivity is a key to pursuing sustainable development, with which the participation of external and indigenous actors as partners aims to “leave no one behind.” At this stage, this study confirms that the technology being designed derives from sufficient scientific knowledge, but it is also easy to construct by its potential users. It provides practical evidence to the conceptual work of Sianipar et al. (2013a), who urged engineers (technology designers) to avoid marginalizing target users. The work suggested adapting typical engineering problem solving (EPS) approaches to let community members help designers embody their technology design. Then, Nilsson et al. (2014) went further to suggest the involvement of multidisciplinary experts (e.g., social scientists, sociologists, or anthropologists) to help engage local stakeholders in a co-creation process. They advised that the multidisciplinary perspective facilitates the rigorousness of the entire design embodiment process through closer interactions with community members.

In the fourth stage (Field Trials), community members join the process of assessing the technical appropriateness of the embodied technology. As the most basic appropriateness, technical appropriateness ensures the proper functions of the drying technology (Guetti et al., 2010; Mishra et al., 2020; Nukulwar and Tungkar, 2021). The involvement of community members (smallholder farmers) as testers attempts to foster the social license towards the technology. The literature has strongly suggested a continuous strengthening of social license towards a solution that avoids isolation. Hoffmann et al. (2007) stated that researchers should open technological development to informalized experiments (testing) driven by target users. Nilsson et al. (2014) believed that an approach as such anchors the technology being tested to existing community members. Zissman et al. (2014) elaborated in a general manner that an assessment should be flexible, and that the tool (in this case, the trial design) is modifiable to fit the contextual practice of its users. In parallel, this stage involves local experts to guide the testing process, ensuring the proper conduct of every trial
replication. As in the third stage (Design Embodiment), the fourth stage promotes a balanced positioning of experts and non-experts, which has been suggested to promote more inclusive environmental development. Pouw and Gupta (2017) stated that this kind of approach gives first-hand rights to community members to understand any solution provided. It creates equal opportunities for providers and users to examine how the solution works (or should work better). Besides, Fressoli et al. (2014) highlighted the fostering of knowledge co-construction among actors involved. In this stage, co-testing indeed fosters knowledge co-construction through the participation of, in their words, “local” actors and “scientists.” However, community members (testers) are placed as the sole conductors of trials, while local experts take an assisting/guiding role. In this sense, this stage illustrates a different shot through parallel partnership as an alternative to sequential positioning in the third stage.

Then, the last stage (Economic/Environmental Assessment) repeats a similar approach to the first stage (Preliminary Study) that involves all relevant rural stakeholders. This stage ensures that the technology, which has been designed (Stage 2 and Stage 3) and technically tested (Stage 4), can meet the economic and environmental requirements (Stage 1) in addition to the desired technical specifications (Stage 1).

Since the first stage involves all stakeholders, by which designers can listen to their desired requirements toward the technology, it would be fair to have discussions with them again to confirm the economic and environmental appropriateness of the technology. It extends, as suggested by Patnaik and Bhowmick (2020), the sense of ownership and responsibility. In their review, the sense relates to self-reliance and empowerment, supporting the intention of this stage to foster a bottom-up perspective until the last part of the entire design process.

Uddin et al. (2014) highlighted that an approach as such lets users confirm the holistic performance of the technology, which, in this stage, has gone through consistent interactions of foreign-indigenous actors, experts and non-experts, and between local stakeholders throughout the preceding four design stages. At this final stage, the reintroduced participation of local stakeholders puts a stronger emphasis on the bottom-up approach of the entire research. In the literature, the bottom-up approach is preferable for inclusive environmental development, which attempts to develop solutions by taking local concerns into account as the points of departure for and confirmation over the solutions. Fressoli et al. (2014) indicated the necessity to take advantage of existing indigenous knowledge to solve local problems, which also requires fair interactions during the participation of local actors from the beginning until the end of the process. In that sense, this study subtly includes an inclusive environmental development for, in specific terminologies introduced by Sianipar et al. (2013a), ensuring the techno-economic and environmental appropriateness of the technology being provided.

6. Conclusion and implications

Providing environment-friendly technology for rural areas under lack of resources and limited knowledge requires an alternative understanding from typical technology designs for economically resourceful and scientifically knowledgeable users. In general, environment-friendly technologies claim to either produce more negligible environmental impacts or resolve prevailing environmental problems. Despite offering substantial environmental benefits, those technologies typically require higher investment and knowledge to make, use, maintain, and dispose of. This research argues that, for an environment-friendly technology to be feasible in a constrained circumstance as in rural areas, the design process shall consider the context in which the technology would be installed. By taking a 5-stage design process in the case of a solar-powered dryer for smallholder cocoa farmers in Nias, Indonesia, this research proves the possibility of providing an affordable, technically functioning, and environment-friendly technology for a rural context lacking economic and knowledge resources. In other words, this study precisely fills in the research gap at both theoretical and practical levels. This research suggests that economic and knowledge constraints of rural areas make each case of the provision of environment-friendly technology for a rural region unique. The particularity of each rural area requires every provisioning effort to apply the perspective of technological appropriateness. The inclusion of technological appropriateness forms a more bottom-up design process that considers local techno-economic and environmental contexts as the sole basis of the technology design process. In that sense, the understanding shifts from typical environment-friendly technologies to an environmentally-appropriate technology. In the provision of technologies for a rural context, technological appropriateness takes desired technical, economic, and environmental requirements from rural stakeholders as the guiding principles for the technological solution. After the technology is designed, the desired requirements become the basis for assessing the technology’s technical, economic, and environmental appropriateness.

The design process also involves rural stakeholders (i.e., the community, local/external experts, and the government) throughout the stages, in which each stage involves particular stakeholders who can support the interests of the stage. In other words, the technology design begins by listening to, flows by working with, and ends by delivering an environmentally-appropriate technology for these rural stakeholders, fulfilling their desired requirements in the process. In the assessment, this study argues that specific stakeholders shall join the process. Technical assessment takes the form of field trials. It involves community members as the target users of the technology, and local experts to guide the assessment. Meanwhile, economic and environmental assessment involves all stakeholders to assess how the technology fulfills the economic and environmental requirements they desire.

Looking at the results of this study, there are various implications for academics, policymakers, and practitioners. First, this study contributes to the body of knowledge about technology design, particularly in constrained circumstances under a lack of resources and knowledge inadequacy. The contribution lies in the inclusion of technological appropriateness (techno-economic and environment) in the design process of an environmentally-appropriate technology for rural contexts. This study shows that technological appropriateness ensures the inclusion of constrained local contexts into the design process. This study suggests that academics, particularly those dealing with technological provision for constrained contexts, consider including the understanding of technological appropriateness in their research. It ensures that the technologies they provide can effectively address insufficient resources and knowledge. Second, policymakers can learn how this study explores the provision of an environmentally-appropriate technology that is affordable and well-functioning. Furthermore, they can learn how the participation of rural stakeholders is possible throughout the design process. Thus, policymakers can consider covering the issue of technological appropriateness and the participation of stakeholders in policies on the provision of technology for rural areas. Policies as such would help make sure technologies provided for rural stakeholders in the future can involve stakeholders in the design process, can make the targeted process faster, better, and perhaps cheap, are within the economic capability of their users, and can address environmental concerns either passively or actively. Then, practitioners can learn to apply the approach of this study in their cases. Practitioners can focus on how this study gathers technical, economic, and environmental requirements from rural stakeholders, works with them to design, construct, and assess the technology, and provides an environmentally-appropriate technology as a result. Practitioners shall realize that their cases have their particularities, making any approach they intend to use in their studies more critical to consider thoughtfully rather than merely copying/transfering the technology as it is.

Ethical declaration

This study did not involve experiments with humans and/or animals.
Declarations 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 article.

Acknowledgment

C.P.M.S. would like to acknowledge Swisscontact Indonesia for providing financial support to this research through the NIA Project (Nias Income-generation through Sustainable Agriculture). C.P.M.S. also expresses his gratitude for the support from those involved in the NIA project, the Sustainable Cocoa Production Program (SCPP), and the assistance from Swisscontact ROSEA (Regional Office South East Asia).

References

Alam, G.M.M., 2017. Livelihood cycle and vulnerability of rural households to climate change and hazards in Bangladesh. Environ. Manag. 59, 777–791. https://doi.org/10.1007/s00267-017-0826-3.

Alam, G.M.M., Alam, K., Mushtaq, S., 2017. Climate change perceptions and local adaptation strategies of hazard-prone rural households in Bangladesh. Clim. Risk Manag. 17, 52–63. https://doi.org/10.1016/j.crm.2017.06.006.

Arnall, A., 2019. Resettlement as climate change adaptation: what can be learned from state-led relocation in rural Africa and Asia? Clim. Dev. 11, 251–263. https://doi.org/10.1080/17565529.2018.1447299.

Arnell, N.W., Lowe, J.A., Challinor, A.J., O’Shorn, T.J., 2019. Global and regional impacts of climate change at different levels of global temperature increase. Climatic Change 155, 377–391. https://doi.org/10.1007/s10584-019-02464-y.

Barry, J., 2012. The politics of actually existing unsustainability: human flourishing in a climate-changed, carbon constrained world. Polit. Actually Existing Unsustain.: Human Flourishing Clim. Changed Carbon Constrained World 1–352. doi:https://doi.org/10.4037/1936-3524.16.1.20120529.

Benevolenza, M.A., DeRigge, L.A., 2019. The impact of climate change and natural disasters on vulnerable populations: a systematic review of literature. J. Hum. Behav. Soc. Environ. 29, 266–281. https://doi.org/10.1300/J171v29n04_16.

Birch, A., Hon, K.K.B., Short, T., 2012. Structure and output mechanisms in design for environment (DFE) tools. J. Clean. Prod. 35, 50–58. https://doi.org/10.1016/j.jclepro.2012.05.029.

Bishop, C.P., 2021. Sustainability lessons from appropriate technology. Curr. Opin. Environ. Sustain. 49, 50–56. https://doi.org/10.1016/j.cousust.2021.02.011.

Boholan, A., Prutzer, M., 2017. Experts’ understandings of drinking water risk management in a climate change scenario. Clim. Risk Manag. 16, 133–144. https://doi.org/10.1016/j.crm.2017.01.003.

Bovea, M.D., Pérez-Belis, V., 2012. A taxonomy of ecodesign tools for integrating environmental requirements into the product design process. J. Clean. Prod. 20, 50–61. https://doi.org/10.1016/j.jclepro.2011.07.011.

Bowonder, B., 1979. Appropriate technology for developing countries: some issues. Technol. Forecast. Soc. Change 15, 55–67. https://doi.org/10.1016/0040-1625(79)90065-9.

Braun, M. and Bauer, A.M., 2016. Remotely designed Appropriate Technology for emergency disaster response in Nepal. Procedia Eng. 159, 275–283. https://doi.org/10.1016/j.proeng.2016.08.179.

Campbell, B.M., Vermeulen, S.J., Aggarwal, P.K., Corner-Dolloff, C., Girvetz, E., Loboguerrero, A.M., Ramirez Villegas, J., Rosenstock, T., Sebastian, L., Thornton, P., K., Wollenberg, E., 2016. Reducing risks to food security from climate change. Global Food Secur. 11, 34–43. https://doi.org/10.1016/j.gfs.2016.06.002.

Carlsen, H., Dreborg, K.H., Godman, M., Hansson, S.O., Johansson, L., Wikman-Granlund, A., 2009. Assessing the sustainability of buildings using a Delphi method: a critical review. In: Medina, E., Marques, I. da C., Holmes, C. (Eds.), Beyond Imported Magic: Essays on Science, Technology, and Society in Latin America. MIT Press, Cambridge, US, pp. 47–63.

Cans, J.S., 1998. Industrialisation with a menu of technologies: appropriate technologies and the ‘big push’. Struct. Change Econ. Dyn. 9, 233–248.

Garniati, L., Owen, A., Krijnsen, V., Wibisono, I., 2014. Interface between sustainable development and technology management in a climate change scenario. Clim. Risk Manag. 16, 133–140. https://doi.org/10.1016/j.crm.2017.06.006.

Gupta, A.K., Sinha, R., Koradia, D., Patel, R., Parmar, M., Rohit, P., Patel, H., Patel, K., Chanyas, V.S., James, T.J., Chandan, A., Patel, M., Prakash, T.N., Vivekanandan, P., 2003. Mobilizing grassroots’ technological innovations and traditional knowledge: values and institutions: articulating social and ethnic capital. Futures 35, 975–987. https://doi.org/10.1016/S0016-2361(03)00056-4.

Gupta, J., Pouw, N.R.M., Ros-Tonen, M.A.F., 2015. Towards an elaborated theory of inclusive development. Eur. Dev. Res. 27, 541–559. https://doi.org/10.1057/eldr.2015.30.

Gyampoh, B.A., Amisah, S., Idinoba, M., Nkem, J.N., 2009. Using traditional knowledge to cope with climate change in rural Ghana. Unasylva 60, 70–74. https://doi.org/10.1002/j.foodchem.2011.01.039.

Hansen, J., Meinzer, O., Metz, P., 2016. Enabling community-powered co-innovation by connecting rural stakeholders with global knowledge brokering: a case study from Nepal. In: Moore, M., Kohler, A., Haider, D.P., Barnes, P.W., 2019. Comparing the impacts of climate change on the responses and linkages between terrestrial and aquatic ecosystems. Sci. Total Environ. 682, 239–246. https://doi.org/10.1016/j.scitotenv.2019.05.024.

Hani, U., Setyagung, E.H., Azadzina, I., Sianipar, C.P.M., Ishii, T., 2013. Preserving cultural heritage: the harmony between art idealism, commercialization, and Triple-Helix collaboration. Am. J. Tourism Manag. 2, 22–28. https://doi.org/10.5921/tourj20130201.

Hansen, J., Hellin, J., Rosenstock, T., Fisher, E., Cairns, J., Stirling, C., Lamanna, C., van Etten, J., Rose, A., Campbell, B.M., 2019. Climate risk management and rural poverty reduction. Agric. Syst. 172, 28–46. https://doi.org/10.1016/j.agsy.2018.01.019.

Hausschild, M.Z., Jeswiet, J., Alting, L., 2004. Design for environment - do we get the focus right? CIRP Annals 53, 1–4. https://doi.org/10.1016/S0007-8506(06)70631-3.

Hayes, K., Blashki, G., Wiseman, J., Burke, S., Reifels, L., 2018. Climate change and mental health: risks, impacts and priority actions. Int. J. Ment. Health Syst. 12, 1–12. https://doi.org/10.1186/s13279-018-01026-0.

Hester, Y.P., Pascawati, N.A., 2021. Problem and technology solution improving water quality in Morotai Island (A case study in Koloray, Muhajirin and Juanga). Technol. Forecast. Soc. Change 12, 9–15. https://doi.org/10.1016/j.techsoc.2021.101552.

Hini, C.L., Law, C.L., Coke, M., 2008. Modelling of thin layer drying kinetics of cocoa beans during artificial and natural drying. J. Eng. Sci. Technol. 3, 1–10.

Hoffmann, V., Probst, K., Christoph, A., 2007. Farmers and researchers: how can collaborative advantages be created in participatory research and technology development? Agric. Hum. Val. 24, 355–368. https://doi.org/10.1016/j.aghum.2006.07.002.

Huy, C.T., 2006. The role of university in promoting indigenous knowledge systems in Vietnam. In: 2nd International Appropriate Technology Conference - July 12-15, 2006 Bulawayo, Zimbabwe, pp. 1–7.

Kaveh, M., Abbaspour-Gilandeh, Y., Nowacka, M., 2021. Comparison of different drying techniques and their carbon emissions in green peas. Chem. Eng. Process. Process Intensif. 160, 108274. https://doi.org/10.1016/j.cep.2020.108274.
Wicklein, R.C., 2013. Design criteria for sustainable development in Appropriate Technology: technology as if people matter. In: Proceedings of the International Technology and Engineering Educators Association, Athens, US.

Wiendahl, H.P., 1981. Five years experience with VDI 2222 guideline in a large capital equipment enterprise. Des. Stud. 2, 165–170. https://doi.org/10.1016/0142-694X(81)90071-5.

Wihardjaka, A., Harsanti, E.S., Sutriadi, M.T., 2019. Anticipate of climate change impacts in rainfed lowland rice through applying Appropriate Technology. IOP Conf. Ser. Earth Environ. Sci. 393, 012098. https://doi.org/10.1088/1755-1315/393/1/012098.

Williams, R., Edge, D., 1996. The social shaping of technology. Res. Pol. 25, 865–899. https://doi.org/10.1016/0048-7333(96)00885-2.

Witjaksono, J., 2016. Cocoa farming system in Indonesia and its sustainability under climate change. Agric. For. Fish. 5, 170. https://doi.org/10.11648/j.

Xenarios, S., Gafurov, A., Schmidt-Vogt, D., Sehring, J., Manandhar, S., Hergarten, C., Shigaeva, J., Foggin, M., 2019. Climate change and adaptation of mountain societies in Central Asia: uncertainties, knowledge gaps, and data constraints. Reg. Environ. Change 19, 1339–1352. https://doi.org/10.1007/s10113-018-1384-9.

Yu, M., Ruggieri, E., 2019. Change point analysis of global temperature records. Int. J. Climatol. 39, 3679–3688. https://doi.org/10.1002/joc.6042.

Zisman, M.A., Evans, J.E., Holcomb, K.T., Jones, D.A., Kercher, M.R., Mineweaser, J.L., Schiff, A.C., Shattuck, M.M., Gralla, E.L., Goentzel, J., Heatherly, C., Czarnik, J., Rodgers, A., Wooten, A., Brennan, M., Mach, O., Cleaves, A., Hartnett, M., Simon, G., Ivers, L.C., 2014. Development and use of a comprehensive humanitarian assessment tool in post-earthquake Haiti. Procedia Eng. 78, 10–21. https://doi.org/10.1016/j.

ˇZurovec, O., Cadro, S., Sitaula, B.K., 2017. Quantitative assessment of vulnerability to climate change in rural municipalities of Bosnia and Herzegovina. Sustainability 9, 1–18. https://doi.org/10.3390/su9071208.