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Systematic conceptualisation of existing evidence from developing and emerging countries

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Understanding the diffusion of domestic biogas technologies:

Systematic conceptualisation of existing evidence from developing and emerging countries

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Abstract

Accelerating the diffusion of domestic biogas is considered to be a promising option for reaching the goal of universal access to energy by 2030, particularly for the provision of cooking energy for rural populations in developing countries. The aim of this study is to develop a systematic account of the factors that influence the diffusion of domestic biogas technologies. To achieve this objective, a three step analysis approach is applied. In the first step, a conceptual model is built based on insights from scholars that have been studying the diffusion of energy innovations in rural contexts. In the next step, a qualitative content analysis of scientific literature is undertaken to test and refine the categories proposed by the conceptual model and to systematically organise the empirical evidence of the factors that influence the diffusion of domestic biogas in developing and emerging countries. The systemised evidence is used to identify the components and interactions between the household configurations and socio-economic context that determine both the adoption process at household level and the overall technology diffusion. Finally, in the last step, we reflect on the implications of the resultant systematic conceptualisation regarding the purpose and design of programmes promoting the dissemination of domestic biogas technologies.

Keywords: domestic biogas, biodigester, developing countries, cooking energy, socio-technical transitions, innovation diffusion

1 Introduction

Domestic biogas is considered to be a clean cooking alternative for the rural poor in developing countries. Accordingly, accelerating the diffusion of domestic biogas plants is expected to significantly contribute to achieving the ambitious goal of ensuring universal access to modern energy services by 2030 [1]. Domestic biogas is not, however, a new idea and first initiatives developing practical designs appropriate for single households or farmers can be traced back to the first half of the 20th century[1]. There has even been mass dissemination of the technology in some Asian countries for decades. For example, more than 26 million plants had been installed in China by 2006 [5]; in India around 4.75 million plants were reported to have been installed by 2014 [6]; and from 1992 to 2013 over 260,000 plants were installed in Nepal [7]. These programmes have been dependent on the continuous and long-term political support from central governments and have led to the emergence of nationwide institutional structures. In contrast, installation rates for domestic biogas plants (the main parameter for measuring the diffusion process) are somewhat marginal in countries where such programmes have not been established. However, global interest in broadening the diffusion of domestic biogas has been growing and during the last decade national biogas programmes have been launched in some Asian, African and Latin American countries.

Domestic biogas refers to the application of anaerobic digestion in order to provide an individual household (generally rural) with services such as the treatment of wastewater and the supply of fuel for domestic use (e.g. cooking). The central component of a domestic biogas plant is the digester (also called the biodigester), which is the container where the anaerobic decomposition of organic matter takes place. There are numerous types of digesters, which vary (among other characteristics) in their geometry, construction materials and installation requirements. [8,9] Digesters for domestic applications are commonly no larger than 10 m^3 (see Table 4). In addition to the digester, a biogas plant comprises other components, such as pipes, valves and additional containers (e.g. for feeding purposes and for the storage of treated slurry).[10,11]

Critical assessments of the suitability of such technical configurations to improve the livelihood of the rural poor, as well as of the effectiveness of mass dissemination programmes, have been emerging. One notable strand of criticism contests the general assumption that domestic biogas technologies are appropriate for addressing the developmental needs of the poorest. Indeed, the applicability of biogas technologies is constrained by access to specific resources such as water, manure, land and financial capital. Insufficient levels of these resources are more likely to be found in poor households. [3,12,13] Another area of controversy is related to the adequacy and effectiveness of programmes fostering the mass dissemination of the technology. One central concern is the lack of individual motivation in the diffusion process; the high rate of diffusion achieved by successful programmes has been driven by concrete plant installation targets and corresponding subsidy schemes, whereas user commitment and

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[1] Some examples of early designs and applications include the patented design and its commercialisation by Mr Lo Guo-Rui in the 1930s in China [2], first installations of early designs under real conditions in Indian rural households during the 1950s [3] and the demonstration of the technology at a school in 1955 in Kathmandu, Nepal [4].

motivation to adopt the technology remains low [14–16]. Related to this, poor user management practices and a lack of follow-up services (e.g. maintenance) are often reported, which lead to malfunction or, in the worst case scenarios, abandonment of the systems [16–20]. The actual number of functional plants (behind the impressive total installation figures) is often unclear. Chen et al. estimate that, "of the 26.5 million biogas digesters in China's rural areas, only 60% … were operating normally" [5]. In India, the rate of "acceptance" of installed plants varies between 40% and 70%, according to Bhat et al. [16].

Although interest in broadening the global diffusion of domestic biogas has been growing, systematic understanding of the particular factors and specific circumstances which result in successful programmes is still lacking. This is relevant because domestic biogas programmes are expected to disseminate the technology under different environmental, social, economic and political conditions. Therefore, the central objective of this study is to develop a systematic description of the factors that influence the diffusion of domestic biogas technologies. The research comprises three stages. (i) In a first stage a conceptual model is developed in order to analyse the diffusion process of domestic biogas in developing and emerging countries. For this aim we build on insights from academics who have studied the diffusion of rural household innovations, particularly the case of energy for cooking, by adapting and complementing their conceptualisations and, thereby, further advancing the concept by taking into account the socio-technical particularities of domestic biogas technologies. (ii) In a second stage the proposed conceptual model is used to organise the empirical observations reported by studies analysing domestic biogas dissemination programmes in different geographical contexts. This step serves two purposes; on the one hand to test and refine the model against available empirical evidence, while – on the other hand – complementing the proposed conceptualisations through the systematisation and description of factors that proved to be particularly influential for the reviewed empirical processes. (iii) In a final stage we reflect on the implications of the resultant systematic conceptualisation regarding the purpose and design of programmes promoting the dissemination of domestic biogas technologies.

2 Conceptual Framework – a system perspective on the diffusion of domestic energy innovations

The process by which households in developing countries change their pattern of domestic energy consumption has long been the object of research by scholars from different disciplines. The simplest conceptualisation is the so-called 'energy ladder' hypothesis [21,22]. While the energy ladder was extensively applied by studies on domestic energy transitions in the 1990s and 2000s, evidence highlighting deficiencies of the model accumulated and some scholars started to emphasise the need to abandon the idea of 'fuel switching' (which derives from the straightforward application of the energy ladder hypothesis), as well as other oversimplifications of adopters' behaviour [23–26].

Accordingly, Ruiz-Mercado and her colleagues developed more comprehensive models of the process by which new energy devices and practices are adopted by members of a given social system [27]. Their analysis is focused on the adoption and diffusion of so-called improved cook stoves (ICS), i.e. stoves that allow the use of traditional biomass fuels, like firewood and charcoal, but whose designs reduce the negative impacts linked to cooking with open fires or traditional stoves, particularly indoor pollution, poor health, deforestation and climate change. The basic assumption of their model is that the adoption of a new cooking device is a process which "takes place in a dynamic system with strong interactions between the user, the technology, the fuels and the larger socio-economic and ecological contexts". The introduction of the new stove in a household initially disrupts the existing dynamic system and the adoption is the process by which a new state of equilibrium is achieved. The outcome is a modified set of cooking practices, in which each fuel-stove option available is applied where it performs best as perceived by the user. For instance, the preferred fuel-stove option for boiling might differ to that frying or grilling.

The system perspective proposed by Ruiz-Mercado and her colleagues shifts the focus from the fuels or the stoves to the user's cooking system. The cooking system comprises material components (fuels, stoves, kitchen etc.) and non-material elements (practices, traditions etc.). The goal of preparing cooked meals is achieved through the interaction between these two kind of elements. This model is able to reproduce the coexistence of multiple stove-fuel options – evident from several studies in different countries – and moves the emphasis from the initial adoption of the new device to its actual use over time. In order to apply this system perspective to the case of domestic biogas innovations we propose to broaden the model in two ways; the first relates to the socio-technical differences of the innovations considered and the second aims to generate a more differentiated conceptualisation of what Ruiz-Mercado and her colleagues referred to as 'the larger socio-economic context'.

Socio-technical differences between ICS and domestic biogas

While the anticipated impacts of the adoption and sustained use of ICSs are diverse, the direct effects on the 'dynamic system' that frames a household's daily life are mostly limited to the domain of cooking practices. The effects of introducing domestic biogas technology into a household are more diverse. Firstly, its application involves not only a new stove in the kitchen, but also the installation and operation of the digester that produces the fuel (the biogas), as well as auxiliary devices for feeding it and handling the effluent, and the pipes for transporting the gas to the kitchen. In other words, as well as becoming the user of a new stove, the user of a domestic biogas system also becomes an energy producer; i.e. the operator of the biochemical process that produces the biogas as well as the 'by products' (liquid effluent and sludge) of the anaerobic digestion. Secondly, domestic biogas is often promoted as a technical solution with a variety of benefits for a household in addition to energy for cooking. The most notable benefits are the provision of biological fertiliser, the adequate treatment of waste water and improvements to sanitation. Therefore, applying the system perspective to the case of domestic biogas requires a more differentiated conceptualisation of the 'dynamic system' in which the user is embedded and in which the new technology is expected to be integrated. Adopting a domestic biogas plant does not only entail adjustments to a household's cooking subsystem. During the process, adjustments between and within the household's other subsystems[2] may be necessary; particularly those related to

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[2] We opt to use the term 'subsystem' to refer to a set of interacting components which fulfils comprehensible single functions, which in turn contribute to constructing and/or sustaining a household's livelihood. Subsystems can be part of a household's own configuration (e.g. those providing cooked meals or crops) or can be external (e.g. those providing knowledge, training or loans).

animal husbandry (which provides the inputs for the anaerobic digester) and crop production (where the use of effluents should generate additional benefits). Therefore, as a minimum, our model should also consider the household subsystems relating to animal husbandry, crop production and sanitation.

Elaborating on 'the larger socio-economic context'

Several studies have emphasised the importance of the socio-economic context in the diffusion of domestic energy innovations, i.e. factors that lie beyond the configuration of individual households. For instance, when analysing their results on domestic energy transitions in Maun, Botswana [26], Hiemstra-van der Horst and Hovorka noted that "structural factors such as policies and market trends at national, regional or even international scales can be critical influences on [households'] energy-use decisions". Based on an extensive review of case studies, Brass et al. highlighted five factors as being particularly influential for the technical success of distributed (electric power) generation projects: "appropriately chosen technology, adequate financing and payment arrangements, ongoing end users' involvement, and supportive national policies" as well as "institutions for collaborative governance"[28]. Our previous research, which focused on small-scale energy projects, identified similar factors determining the performance of energy initiatives rooted at community level [29] and highlighted the importance of the knowledge and skills of the implementing organisation as facilitators of the socio-economic transformation necessary for the adoption of new energy solutions at community level. [30]

For the study of the domestic biogas diffusion process, useful insights on the influence of structural factors can be found in Agarwal's work on the diffusion of innovations in rural contexts [31]. Her analysis emphasises how a user's ability to gain access to 'external' resources, such as knowledge, credit or inputs, is a strong determinant of the user's ability to adopt new technology. In order to improve the understanding of the diffusion process of biogas plants, consideration should be given to the institutional settings which determine how resources are allocated and exchanged amongst users and other actors involved in the process. Consequently, we propose studying subsystems which exist beyond the individual household configuration, particularly those subsystems that provide the knowledge, financial capital and technical input required to ensure that a user can learn about, invest in, operate and draw benefit from a domestic biogas plant.

In summary, we present a conceptual model to understand the dynamic processes triggered by the introduction of a domestic biogas plant into an individual household, which considers two types of interacting subsystems. The first subsystem relates to the functioning of the household's internal livelihoods assets. Under this set we propose considering those subsystems related to (i) cooking, (ii) crop production and (iii) animal husbandry, which appear to be the most directly related to the functionality of domestic biogas technology. The second set of subsystems refers to functions which are largely dependent on the socio-economic context of the user. Under this second set particular attention is paid to subsystems which determine the ability of users to access (iv) knowledge about domestic biogas technology; (v) finance for the investment required and (vi) the necessary supply of technical inputs (skills and materials) for designing, constructing and installing the domestic biogas plants. Figure 1 provides a schematic view of this conceptualisation. The basic assumption is that the installation of a domestic biogas plant changes the current conditions of a household's subsystems. The reciprocal interaction between the user, the newly-installed biogas plant, the household configuration and the socio-economic context determines the actual usage of the new technology and, ultimately, its impact on the user's livelihood. Successful diffusion depends on adjustments within the subsystems being made in such a way that the functionality of the domestic biogas technology can be effectively achieved and the expected benefits can be derived by a large set of users.

<insert Figure 1 here>

3 Methods and materials

Qualitative content analysis of scientific literature is undertaken to examine empirically observed manifestations of the interactions between the domestic biogas plant, the user, the household and the socio-economic context. The aim of the analysis is twofold; firstly to test and refine the categories of the conceptual model proposed in section 2 and, secondly, to systematically organise the evidence of the factors that influence the diffusion of domestic biogas in developing or emerging countries. Influential factors are identified and clustered by examining similarities and relationships between single observations from different case studies. The resultant systemised factors present the basis for the detailed descriptions of the components and interactions between the household configurations and socio-economic context that determine both the adoption process at household level and the overall technology diffusion.

3.1 Selection and description of the literature

Empirical findings on the factors that influence the diffusion of domestic biogas technology are the basis for the analysis. Accordingly, studies examining the conditions and results of single projects or complete programmes aimed at disseminating domestic biogas plants in developing or emerging countries were considered. Only studies that appeared in publications validated through a peer review process were included.

The selection process comprised several stages. The Scopus databank was used to screen the literature initially. The terms "biogas", "digester" and "biodigester" were combined with the terms "domestic" and "household" to screen titles, abstracts and key words. In order to refine the search, articles published in journals dedicated to research on biochemistry, engineering, mathematics, medicine and similar issues were excluded. At the time of the screening (August 2014) this search resulted in 509 titles. In a further step, the titles – and eventually abstracts – were reviewed by the authors in order to further refine the list according to two criteria: geographical scope and object of study. Only studies that claimed to study field experiences from biogas dissemination initiatives in developing and emerging countries were considered. As a result, much of the literature, which focused on technological engineering, feasibility studies and projections of performance and potentials, was excluded. Ultimately, this resulted in a sample of 50 studies published between 1998 and 2014. The authors then examined the research objectives and methods applied by each study. The aim was to identify studies which considered (at least to some extent) the context in which users gain knowledge, make decisions, invest in, operate and use the products from domestic biogas plants. Finally, 23 studies were selected for in-depth analysis (listed in Table 1).

Table 1 Studies selected for in-depth analysis

Short citation	Ref. no.	Country	Study area	No. of households surveyed	Comparison of users/non-users

Kabir et al., 2013	[32]	Bangladesh	4 Districts from Dhaka, Rajshahi and Rangpur	300	yes
San et al., 2012	[33]	Cambodia	50 villages in Kampong Chhnang province	767	no
Gosens et al., 2013	[34]	China	38 villages in Gansu, Guangxi, Hubei and Shandong provinces	1065	yes
He et al., 2013	[35]	China	12 villages from three 'cities' of Shandong Province	473	yes
Huanyun et al., 2013	[19]	China	41 villages from 8 towns in the Yuxi region, Yunnan province	797	no
Qu et al., 2013	[36]	China	32 villages in 8 counties in Gansu, Guangxi, Hubei and Shandong provinces	1227	yes
van Groenendaal and Gehua, 2010	[37]	China	3 villages in Gansu and Sichuan provinces	239	yes
Xiaohua et al., 2007	[38]	China	Lianshui in Jiangsu province and Guichi in Anhui province	696	yes
Bhat et al., 2001	[16]	India	25 villages in Sirsi, Karnataka state	187	no
Raha et al., 2014	[39]	India	8 villages in 2 districts of Assam	60	no
Mwirigi et al., 2009	[40]	Kenya	Nakuru and Nakuru North districts	200	yes
Cheng et al., 2014	[20]	Nepal	Nationwide field study	94	no
Katuwal and Bohara, 2009	[41]	Nepal	Nationwide biogas user survey 2007/2008	461	no
Garfí et al., 2012	[42]	Peru	Department of Cajamarca	12	no
Laramee and Davis, 2013	[43]	Tanzania	7 communities northwest of Arusha town	40	yes
Mwakaje, 2008	[44]	Tanzania	4 villages in the Rungwe district	200	yes
Walekhwa et al., 2009	[45]	Uganda	6 districts of central and eastern Uganda	220	yes
Thu et al., 2012	[46]	Vietnam	Quoc Oai district in Hanoi and Huong Tra district in Hue province	181	yes
Martí-Herrero et al., 2014	[47]	Bolivia	Nationwide programme	-	-
Buysman et al., 2013	[48]	Cambodia	Nationwide programme	-	-
Chen et al., 2010	[5]	China	Nationwide programme	-	-
Chen et al., 2012	[49]	China	Nationwide programme	-	-
Landi et al., 2013	[50]	Rwanda	Nationwide programme	-	-

Regarding the scope of the analysis, the studies can be grouped into two categories: i) studies evaluating the implementation and/or impact of biogas dissemination through data collection at household level and ii) studies evaluating the lessons learned from nationwide dissemination programmes from an overarching perspective.

The first group comprises 18 studies. Although the aims and methodologies vary, all are based on detailed surveys of single households. The sample sizes vary between 12 households in a small programme addressing rural Andean communities in Peru [42] to 1227 households from four different provinces in China [36]. Some of these studies comprise additional interviews with other stakeholders, such as government officials, technicians or NGO staff, to complement the information. Most of these studies aim to assess the effects of the technology on diverse dimensions of household livelihoods, but none provide data on the user situation prior to implementation (baseline data). Instead, a commonly-used approach is to compare data from users and non-users of biogas plants. This approach is applied by eleven of the reviewed studies. Three explicitly aim to assess problems and failures in the performance of the installed systems and another three focus on analysing factors affecting users' decisions to adopt the technology.

Among the studies describing lessons learned from nationwide programmes, two explicitly indicate that interviews with different actors involved in the development of the programme were part of the data collection process [48,50]. The two papers reviewing the development of biogas technology in China are mainly based on Chinese literature about the topic [5,49]. Finally, one article documents the experiences from a nationwide biogas programme in Bolivia active between 2007 and 2012 [47].

3.2 Coding and categorising

Our analysis combines both deductive and inductive category formation. The integration is achieved by applying 'axial coding': "the categories that are most relevant to the research question are selected from the [inductive] developed codes and the related code notes. Many different passages in the text[s] are then sought as evidence of these relevant codes in order to elaborate axial categor[ies]" [51]. For our analysis the set of subsystems outlined in the conceptual framework (see section 2) serve as the deductive categories. Inductive category formation is applied to identify factors and mechanisms determining the interaction between the technology, the a priori formulated subsystems or other relevant domains framing households' decisions and actions. Thus, the relevance of statements and codes is evaluated by their ability to describe or explain interactions between the user and the domestic biogas technology.

In a first stage, the studies are reviewed in detail. The main focus is on observations about physical, practical and institutional components that influence the adoption process at household level, i.e. factors affecting the decision to adopt (or not) a biogas plant, the operation and maintenance of the installed plant, the actual use of the products (biogas and effluent) and the perception of the benefits. Reported observations are extracted as single statements with unambiguous meanings. Particular attention is given to the empirical source that backs up each statement. The first coding process assigns one 'keyword' to each statement. 'Keywords' are built by selecting one word or combining several words present in each statement. Keywords refer to one aspect that is observed as relevant to the domestic biogas diffusion process in each sentence. The reviewed studies stem from different epistemic and reference systems (e.g. disciplines, cultural settings and socio-political context), which becomes evident in the variety of terms used to refer to the same subject or describe aspects of a given issue. For instance, the terms ‘financial assistance’, ‘payment’ or a share of ‘investment’ assumed by a donor organisation are used to describe the particularities of the applied subsidies. Another illustrative example concerns the terms used to refer to the use of stalls for animal husbandry practices: ‘animal pen’, ‘zero-grazing’, ‘indoor-fed’. Thus, keywords are firstly grouped into more general first-order codes with unified meanings. The aim here is to identify influential aspects that have been observed in several studies (disregarding the terminology used by the authors) and to elaborate codes that best represent those common observations.

In a second aggregation step, the analysis looks for functional relationships between first-level codes in order to create more aggregated categories (second-level codes). This time the relationship between codes is not given by the similarity of meaning but by their role in the realisation of specific tasks/functions of the domestic biogas technology, the user’s household/farm or the socio-economic context. For instance, according to the collected observations, the animal type is strongly related to the use of stalls which, in turn, is related to the user’s ability to ensure regular feeding of the digester and the degree to which it is a laborious process. We grouped these related observations under the category ‘husbandry practices’. At this level of aggregation the influential factors are derived from the reviewed literature. Subsequently, an assessment is made as to whether the developed codes can be related to the functionality of one (or several) of the a priori formulated subsystems, or whether they might refer to subsystems that are not considered by the proposed conceptualisation of domestic biogas diffusion. The coding process is not linear. It implies a recursive procedure, where the suitability of codes and categories is challenged by re-evaluating their ability to incorporate observations from several studies. This recursive process forms the basis for building a detailed description of the dynamic system in which the adoption of domestic biogas takes place and, more specifically, for describing the household subsystems and their socio-economic contexts which are influential to the diffusion of the technology. Table 2 illustrates the results of this coding process by presenting the set of first and second-level codes clustered into two of the a priori formulated subsystems, i.e. animal husbandry and crop production.

Table 2 Resultant set of first and second-level codes clustered into the animal husbandry and crop production subsystems

1st level code	2nd level code	Subsystem
Labour	Husbandry practices	Animal husbandry
Type of animals		
Use of stalls		
Wastewater regulation		
Number of animals	Number of animals	
Bought manure		
Use of water	Use of water	
Feeding preparation	Feeding preparation	
Awareness of effluent value	Cognitive factors	Crop production

Effect of effluent	
Effluent management	
Distance to fields	Physical constraints
Farm size	
Manure as fertiliser	Existing fertilising practices
Use of synthetic fertilisers	

Applied to the 23 selected studies, the analysis led to the extraction and classification of 382 sentences (Table 3). The vast majority of the extracted observations can be related to the functionality of at least one of the a priori formulated subsystems that configure users' households and their socio-economic context. However, only a few useful statements about the interaction between domestic biogas and the household sanitation situation were found. The information contained in those statements does not allow for generalisation about factors and mechanisms influencing the diffusion process of domestic biogas. Moreover, only a small group of statements (19) refers to aspects that cannot be related to the a priori formulated subsystems. These observations suggest possible interactions with four additional subsystems: research and development, water supply, heating, and lighting. However, once again the information in these statements is limited and does not allow for elaborated descriptions of the factors and mechanisms regulating their interaction with domestic biogas technology.

Table 3 Quantity of sentences coded and classified according to their affiliation to household subsystems or socio-economic context

Subsystem	**Coded statements**
Cooking	83
Finance	64
Animal husbandry	58
Promotion & Education	53
Crop production	51
Technology supply	44
Sanitation	12
Research & Development	6
Water supply	4
Heating	4
Lighting	3
Total	382

4 Analysis and results – influential factors for domestic biogas diffusion

This section presents detailed descriptions of the factors and mechanisms observed to influence the integration of domestic biogas technology in six subsystems that configure users' households and their socio-economic context, i.e. cooking (the daily preparation of meals), animal husbandry, crop production, promotion and education (access to information and training), finance (improving financial capacity) and technology supply (supply of materials, equipment and technical services). Figure 2 summarises these findings in a schematic way. The situation depicted by the graphic is one in which successful integration is achieved. This, in turn, is characterised by positive/beneficial outcomes from the household's point of view.

<insert Figure 2 here>

4.1 Cooking

The use of biogas to replace the formerly used cooking fuel is the main anticipated outcome of the successful adoption of domestic biogas technology. However, rarely is the previously used fuel wholly replaced. One notable exception is given by Bath et al., who highlight that "85% of the [surveyed households] reported that all their normal daily cooking energy needs were met through biogas" [16]. Partial substitution, i.e. the adoption of biogas as an alternative fuel for cooking, is the most commonly reported outcome. The *type of fuels* used before (and after) the adoption of biogas and particularly the extent to which they can be *commercially procured* are the most prominent factors influencing this outcome. Additionally, the *seasonality* and the *quality of the biogas stoves* also influence the relationship between domestic biogas adoption and the user's cooking subsystem.

4.1.1 Types of fuels and fuel procurement

Non-commercial fuels are the primary source of domestic energy in all the studies. Firewood is prominent among the non-commercial fuels. It is part of the average energy mix for domestic use in all cases. The share of firewood in the energy mix, as well as the use of other non-commercial energy carriers, depends on local conditions and farm activities. For instance, total reliance on firewood is found by Garfi et al. in their case study of a Peruvian Andean village, where "in the previous scenario [without biogas plant] the families involved in the pilot project only used firewood" [42]. As well as firewood, agricultural residues such as straw and stalk are often part of the energy mix in rural Chinese households; however, the share of these energy carriers varies from province to province [38] and even from village to village [37].

In addition, a wide range of *commercial* fuels, mainly fossil fuels, are present in the energy mix in rural households, such as liquefied petroleum gas (LPG), kerosene, charcoal and coal. Once again, broad variations are found according to local conditions. Coal is particularly prominent in rural Chinese households, while in African countries charcoal and kerosene are the most commonly used commercial fuels. Of all the commercial fuels, LPG is the most universally present in the reviewed studies. The use of LPG is reported in China [34,37,38], India [39], Kenya [40], Nepal [41] and Tanzania [43]. However, the actual consumption of LPG is often low and the extensive use of LPG to meet domestic energy needs is unusual.

As well as variations in the share of commercial and non-commercial fuels, there are also variations in unpaid *labour* and monetary *expenses*. The consumption of non-commercial fuels does not necessarily involve monetary transactions, as in most cases access to biomass resources is free (e.g. biomass produced on the farm) and unpaid labour from family members is used for the required processes. Some exceptions are however evident; for instance, when the provision of non-commercial fuels necessitates hiring external labour and permission fees are payable for accessing communal resources [33,43]. However, in general, the procurement of non-commercial fuels has a low monetary cost and relies on financially uncompensated labour-intensive tasks.

The way in which these energy procurement tasks are assigned within a household plays a fundamental role in the adoption process. Regardless of the geographical context, in most of the studies women are reported to be the primary household members responsible for the provision of energy. Workload in terms of time is an often-used indicator to track changes resulting from biomass adoption. The reduction in time spent on fuel collection after installing the biogas plant varies from “not significant” in Dong Huan, China [37] to a 50% decrease in the Peruvian case study [42]. Moreover, women play the main role in the whole cooking subsystem, which includes tasks such as fuel procurement, meal preparation and cleaning the cooking utensils. Therefore, some studies differentiate or include the labour related to these tasks in their analysis. While the reduction in time required for all cooking-related tasks is often documented and quantified, the additional labour required for the operation and maintenance of the biogas plant is not. An interesting exception is found in the survey carried out by He et al. in China. When asked for perceptions on reductions in housework load in general, less than 50% of the respondents gave positive assessments [35].

4.1.2 Seasonality and the biogas stove

In addition to fuel types and their procurement, *seasonality* and the *biogas stove* (or biogas stove quality) play a role in the adoption process. The biogas yield is directly related to the temperature of the substrate within the digester. In regions with pronounced winter seasons, users face significant reductions in biogas yields during wintertime, as reported in some regions in China [35,38] and India [39]. In order to use the biogas for cooking, the adoption of a biogas plant always comprises the provision of a new stove, or the adaptation of the existing one. This requires the user to adopt new practices in operation and maintenance. Only three studies report on observations related to the biogas stoves. All of these refer to difficulties, such as improper maintenance by the users [20] and recurrent need for maintenance [43,46] due to the rapid deterioration of stove components.

4.2 Animal husbandry

Animal manure is the primary source of substrate for domestic biogas plants. Consequently, the integration of the biogas technology with the user’s animal husbandry is central to the adoption process. The desired outcome is to ensure that the digester is continuously fed with appropriate substrate mixture, which requires the redirection of the flow of animal manure (or a fraction of it) to the digester. The *type* and *number of animals* are the most basic influencing factors. However, the actual *configuration* of a household’s animal husbandry has a strong influence on the adoption process; i.e. issues such as use of animal stalls, animal feeding practices and also water usage.

4.2.1 Animal type and husbandry practices

Among the cases described in the reviewed literature, manure from cattle and pigs is the main source of substrate for household biogas plants. A noteworthy difference was found between East Asian countries and other regions. Animal husbandry in China, Vietnam and Cambodia seems to be dominated by pig production, while in Africa, India, Nepal and Bangladesh cattle rearing was almost exclusively documented. This difference is relevant because animal type is directly related to different configurations in animal husbandry practices.

Pig husbandry is more likely to comprise stalls (i.e. pigpens). This makes the availability of manure for biogas production directly dependent on the number of animals. In China, this common feature of pig husbandry has even led to the development of standardised intervention packages, like the so called ‘three-in-one’ model [49]. Consequently, “the investment in the bio-digester is combined with a major renovation of the farm (at least a new kitchen, pigpen, and toilet)” [37].

On the other hand, the actual availability of manure from cattle is influenced by the existing husbandry practices. Most of the case studies from Africa highlight free-grazing as a common practice. Programmes promoting domestic biogas look for farmers who practice ‘zero-grazing’, like in Kenya [40] and Tanzania [43], or those who practice ‘semi-stabled’ husbandry, in which animals are stabled at least at night, like in Rwanda [50]. As a result, dairy farmers, or those who produce milk on a daily basis for self-consumption, are more likely targets for biogas promotion programmes, as illustrated in Tanzania [44] and India [39].

4.2.2 Numbers of animals

The size of the biodigester depends on the daily availability of manure. The biogas promotion programmes studied set minimum standards of between 20 kg per day in the case of Rwanda [50], and up to 50 kg manure per day in the case of India [39]. Accordingly, a minimum number of animals is often a pre-condition for participation. For instance, in Rwanda “at least 4 pigs, 4 semi-intensive (stabled at night) or 2 stall-fed (zero-grazing) cattle … at farm” are the minimum requirements [50], while to apply for national funds in the Chinese programme, “3 pigs per household” is the minimum [34].

Lack of manure is a major cause of failure. In their Nepal study, Cheng et al. found that 10 plants (from a sample of 69) were “underfed or irregularly fed, which is due to the fact that some farmers gave up livestock breeding or decreased the number of animals” [20]. Reduction in the number of animals on the farm and the consequent reduction (or abandonment) of biogas production has also been observed in China [19,37]. Migration dynamics can account for such changes, i.e. young people moving to the city for work, which reduces the labour force in the countryside and impacts on farming activities [19,36,49]. However, insufficient animal manure from the farm does not necessarily hinder the adoption of biogas systems. In their study of villages in Shandong province, China, He et al. reported that 104 households (from a sample of 301) purchased manure for their biogas plants [35].

4.2.3 Water use and feed preparation

As well as the number of animals and the use (or not) of animal stalls, two additional animal husbandry practices which can affect the functionality and effects of biogas plants are worth mentioning: water use and animal feed preparation. Water may be used for the regular cleaning of animal sheds. This can reduce the need for additional water to form the appropriate substrate mixture. However, excess water will reduce the effectiveness of the biogas plant by reducing the decomposition rate of the organic matter and, in turn, the biogas production. This situation was noted by Thu et al. in the provinces of Hanoi and Hue in Vietnam [46]. In contrast, Laramee and Davis observed biogas plants integrated in dairy farms in Northern Tanzania where "cattle urine collected was a sufficient amount of liquid for mixing, and (…) water inputs were minimal" [43].

Another common feature of husbandry practices in stables is that animal feed has to be transported to the stalls and it often requires some sort of preparation. Four of the reviewed studies explicitly recognise the use of biogas as fuel for these feed preparation tasks. For instance, the preparation of mash for pigs requires a cooking process [33,38,46]. Interestingly, Laramee and Davis describe how biogas was used for heating drinking water for cattle during the cold season in Northern Tanzania [43]. These observations give clear indications about linkages between biogas technology and animal husbandry which go beyond mere substrate provision.

4.3 Crop production

Users of domestic biogas plants are generally assumed to be involved in some sort of agricultural activity. Consequently, it is generally expected that the effluent from the anaerobic digestion will provide additional benefit to users as bio-fertiliser, thus increasing crop productivity. The actual application of effluent to a user's crops is the main link between biogas technology and the user's crop production. How this link develops during the adoption process depends on diverse factors that can be grouped into *cognitive* components (e.g. knowledge, awareness and perception of the value of the effluent as a fertiliser), *practice/routine* elements (e.g. use of synthetic fertilisers and effluent management practices) and *physical constraints* (e.g. distribution and distance to crop plots and the liquid nature of the effluent).

4.3.1 Cognitive factors

Although the production of bio-fertiliser is explicitly mentioned as one of the main benefits of domestic biogas in all the reviewed studies, only seven actually note high levels of awareness and/or the actual application of bio-fertiliser in their case study areas [16,32,34,35,41,43,47]. In contrast, other studies identify low levels of awareness leading to low levels of application [19,39], ineffective application [37] or improper management and discharge of effluents [20,46]. Garfi et al. and Martí-Herrero et al. note that a lack of validated knowledge on the fertilising value of effluents for the specific crops cultivated by users, as well as on appropriate application techniques, explains these low levels of application [42,47]. There is little data about the effect of effluent use in terms of crop productivity. This may be partly explained by the methodological difficulty of linking crop productivity to the use of effluent in a sound way, as "too many confounding variables (…) influence this relationship" [34]. However, some studies take the user's own perceptions as an indication of the actual impact of effluent use [41,47].

4.3.2 Existing fertilising practices

Measuring reductions in money spent on fertilisers and pesticides is a proxy variable that is often used to track the use and effect of effluents. An underlying assumption is that the farmers commonly used commercial fertilisers and pesticides prior to the adoption of domestic biogas. However, this is not a general feature of domestic biogas users [44,46,48]. For those farmers who spend significant amounts on commercial fertiliser, the adoption of biogas and particularly the use of effluents can lead to measurable financial savings. Indeed, these financial savings can be greater than the savings made due to the substitution of cooking fuels [34,47]. Nevertheless, it remains the case that cognitive factors can reduce the actual financial effect of effluent application. This is illustrated by one study in China where biogas users applied the effluent in addition to, instead of as a substitute for, commercial pesticides and fertilisers [37].

4.3.3 Physical constraints

The availability and distribution of crop plots strongly influence the actual use of effluents. The development of 'eco-agricultural models' in China illustrates how the distribution of crop plots (and more generally the existence of characteristic production systems) can influence the whole conceptualisation of biogas technology. The popular 'three-in-one' model (previously described) is often related to the production of fruit or vegetables [37,49]. Moreover, extensions to that model integrate investment in greenhouses for vegetable production into one single intervention [5]. In contrast, three studies provide examples of crop production distributed between different plots and at varying distances from the farmers' home, animal stalls and the digesters, in Vietnam [46], Tanzania [43] and Nepal [41]. In such situations the actual use of effluents is influenced by the means of storage, transportation and field application available to users. A common outcome in such situations is a low rate of effluent application, where only small plots near to the home and biodigester, such as kitchen gardens [41] and vegetable patches [46], are fertilised using the effluent. Applying the effluent to plots located far from the digester requires additional equipment and labour [46]. The liquid nature and high dilution rate of the effluent are major disadvantages in comparison to synthetic fertilisers. This, in turn, further reduces the actual potential of the effluent to replace synthetic fertiliser at plots remote from the digester [43,46]. However, the lack of crop land or surplus effluent might not necessarily lead to improper discharge. Raha et al. observed that in one scheme in Assam, India, the effluent is sold "to a local organisation which used it in the production and marketing of vermin-compost" [39].

4.4 Promotion and Education

Domestic biogas is still an unknown and novel technology for many rural households which could benefit from adopting and integrating it into their daily lives. Under the category 'promotion and education', we gathered a cluster of issues reported by the reviewed studies, which point at the flow of 'knowledge' resources that was anticipated by the proposed conceptual model. On the one hand, these knowledge flows aim to raise awareness among potential users and create well-informed households that are able to decide whether or not to invest in the technology. On the other hand, 'promotion and education' includes efforts aiming to build knowledge and skills among users for the appropriate (and continuous) operation and maintenance of the domestic biogas system, in order to enable "informed, engaged user[s] to fully realize and utilize its array of intended benefits" [50]. Promotion and education activities targeted at (potential) users are recognised in most of the reviewed studies as crucial for the diffusion of the technology. Factors reported as influential in this process can be divided into three categories: the *actors* involved in promotion, the *activities and channels* used for promotion and the actual *information and skills* transferred.

4.4.1 Promoting actors

Various state agencies are involved in the planning and implementation of nationwide biogas programmes, which rely on central government support. The role of state agencies is diverse. In general terms, central government entities promulgate supportive policies, overarching goals, standards and financial support schemes, while local state entities implement practical measures and local-specific projects. Central government entities are often ministries or ministerial offices; for instance, the Ministry of Finance, National Development and Reform Commission [NDRC] and Ministry of Agriculture [MOA] in China [49]; the Ministry of New and Renewable Energy (MNRE) in India [39]; the Cambodian Ministry of Agriculture, Forestry and Fisheries (MAFF) in Cambodia [48]; and, in Rwanda, the Ministry of Infrastructure [50].

There is evidence of diverse institutional arrangements to disseminate nationwide policies and goals to the field and to reach the targeted beneficiaries. In China, for instance, a ‘five-level’ hierarchical system of agencies is responsible for the management and promotion of rural energy projects, which includes agencies at national, provincial, city, county and township level [35,49]. In India, in addition to the Ministry of New and Renewable Energy, there are three levels at which the National Biogas and Manure Management Programme is implemented: a) by the ‘State Nodal Agencies’ where targets and subsidy funds are allocated from central government; b) by private companies[3], which are contracted by the state nodal agency in order to undertake biogas plant installation and post-installation maintenance; c) by households which adopt the technology [39]. In Bangladesh, the National Domestic Biogas and Manure Programme is coordinated by the state-owned Infrastructure Development Company Limited (IDCOL). Technical specifications, as well as other regulations for subsidy allocation, are set by IDCOL and donor organisations (SNV and KfW). The actual implementation of biogas plants is assumed by more than 30 partner organisations, which include NGOs and private companies active in rural areas [32].

Non-governmental organisations are often involved in the promotion of domestic biogas among their rural beneficiaries. In Bangladesh “[a]bout 90% of biogas users were motivated for adopting the biogas technology by NGOs” [32]. Similarly, church organisations have been active in biogas promotion in Tanzania [44] and Uganda [45] since the mid-1980s. The pilot project analysed by Garfi et al. in the Peruvian Andes was the combined work of three NGOs active in the region [42].

Farmers’ associations can play a central role in the promotion of domestic biogas. Bhat et al. state that the promotional activities and additional credit options provided by growers’ associations were key factors in creating demand and effective supply structures in Sirsi, Karnataka state in southern India [16]. In Bolivia, farmers’ associations were key in the implementation of the biogas programme analysed by Martí-Herrero et al. These associations operated as executive organisations that “received governmental funds and implemented the project on their own” and/or cooperated directly with the programme implementing agency (the German society for international cooperation, GIZ)[47].

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[3] As well as private contractors, the participation of other types of agencies in the implementation of the NBMMP is foreseen, such as cooperatives, community action groups, NGOs, financial institutions, etc. However, Raha et al. found “very few examples of these agencies playing an active role in the villages (…) visited in Assam”[39]

In countries with established national programmes and financial subsidies, private companies are involved in the diffusion of domestic biogas. Incentivising the participation of the private sector is a common objective of those programmes.

4.4.2 Information and skills

Information about the benefits of the technology is undoubtedly central for raising the awareness and motivation levels of potential users. The range of motivational issues is broad. The provision of adequate responses to pressing environmental concerns at local level can be important; for instance, tackling the problems caused by inappropriate manure management as a motivation to adopt the technology [46] or reducing deforestation pressure [32]. Expectations linked to improvements in household livelihoods are also important drivers. Laramee and Davis found that 40% of their respondents acknowledged the increased scarcity of fuel wood as a motivation for investing in domestic biogas in Tanzania [43]. Based on their observations in China, Van Groenendaal and Gehua claim “that the households regard the renovations and the improved indoor living conditions as the major benefits, and not the financial benefits” [37]. Anticipated economic gain can also play a role. Economic gains are not necessarily, or solely, linked to reductions in energy costs; savings in the cost of fertiliser, as well as simply having the option to access government subsidies, can drive motivation. [32,36]

In addition to the need to increase user motivation, some studies provide clear indications of the need to build users’ knowledge and skills in the operation and maintenance requirements of the technology. Lack of knowledge about the periodical operation and maintenance tasks often causes failure. For instance, from a sample of 94 digesters in Nepal, Cheng et al. identify lack of knowledge about the technology and maintenance as the main cause of low biogas production, failures in the pipeline systems and - more prominently - unsuitable management of effluents [20]. Similarly, Huanyun et al. found that over 60% of the digesters from their sample of 797 in Yunnan province in China were dysfunctional and point to “poor management” by adopters as “the biggest reason” leading to that outcome [19]. The link to promotional activities, in the sense of building technological knowledge and skills and the integration of other subsystems (as previously discussed), is worth mentioning here. An example is the role of cognitive and practical factors in the proper integration of biogas technology into the crop production and animal husbandry subsystems. In this regard, Martí-Herrero et al. also point to the need to consider the workload linked to the adoption of the technology as an integral part of the promotional activities [47].

4.4.3 Activities and channels

Promotional activities can be divided roughly into two groups. On the one hand, mass promotional campaigns aimed at reaching wide audiences using TV, radio and other forms of electronic and printed media are explicitly reported in Bangladesh [32], Cambodia [48], China [36], Kenya [40], Rwanda [50] and Vietnam [46]. On the other hand, more targeted activities such as workshops at village and provincial level, visits to demonstration sites or seminars with locally-active NGOs and associations are reported [47,48,50]. As well as these promotional activities driven by organisations coordinating biogas initiatives, some studies highlight the role of informal channels for disseminating information and increasing motivation [32,46,50]. Moreover, Buysman and Mol cite an attempt to institutionalise this type of promotional activity by implementing projects with “peer to peer user networks” as a mean of promoting and marketing biodigesters in Cambodia [48].

4.5 Finance

From a simple economic perspective, the introduction of a biogas plant is an investment in new capital, which is expected to improve a household's general economic performance and yield a financial return in the form of increased income or savings. A common observation in all the reviewed studies is that the initial *investment cost* of domestic biogas plants exceeds the *investment capacity* of most potential users. Within the finance subsystem, we collated the issues that influence the ability of potential users to make the required financial investment. In addition to the investment cost itself, three additional factors appear to influence whether or not a potential user will invest in a biogas plant. These factors are the availability of *subsidies*, access to *credit sources* and the *actors* providing financial assistance.

4.5.1 Investment costs

Figures relating to initial investment costs are presented in Table 4. The reported costs vary between USD 200 in Vietnam to USD 1155 in Rwanda. Caution should be exercised when making comparisons based on these values. Firstly, most of the studies do not describe what costs are included in the estimation when a household decides to invest in a biogas plant. While it can be assumed that material costs are always considered, only two studies explicitly mention that labour costs for installation are actually included [33,43]. Moreover, costs relating to programme management are probably excluded in all the estimations. The lowest costs are found in Vietnam, Bangladesh and Bolivia. However, these case studies also indicate that initial investment costs are a main barrier for adoption and that "the most common reason associated with not installing biogas plants is lack of money". [46]

Table 4 Selection of investment costs and subsidy levels reported by the studies reviewed

Country	Ref. No.	Reference year (a)	Investment cost [USD]	Subsidy [USD]	Subsidy-cost ratio	Plant size [m^3]
Vietnam	[46]	2012	200	60	0.30	6-8
Bolivia	[47]	2014	220	55	0.25	11.3
Bangladesh (b)	[32]	2013	385	115	0.30	1.4 - 8
China (c)	[35]	2013	456	249	0.55	8
Cambodia	[33]	2012	500	150	0.30	6
India (d)	[39]	2009	722	206	0.29	4
Tanzania	[43]	2011	750	200	0.27	6
Rwanda	[50]	2013	1155	300	0.26	6

(a) Reference year is the year of publication of the corresponding study, except in the case of India and Tanzania where the studies explicitly mention other reference years. (b) Figures for investment cost and subsidy originally given in BDT (30,000 and 9000 respectively); exchange rate 1 USD = 78 BDT is used. (c) Figures for investment cost and subsidy originally given in Yuan (2800 and 1530 respectively); exchange rate 1 USD = 6.14 Yuans is used. (d) Figures for investment cost and subsidy originally given in Rupies (35,025 and 10,000 respectively); exchange rate 1 USD = 48.5 Rs. is used.

4.5.2 Subsidies

All the programmes and initiatives in the studies provided subsidies to cover part of the investment costs. The preferred scheme is that of a 'flat rate', i.e. the provision of a fixed subsidy regardless of the size (and therefore the actual cost) of the selected biodigester. However, different levels of financial assistance can be applied in different geographical regions. For instance, the Chinese and Indian programmes differentiate between geographical regions [6,34]. Interestingly, the majority of the subsidy schemes presented in Table 4 tend to cover 30% of the investment costs for biodigesters of 6m^3. The case in China is noteworthy as the subsidy rate is significantly higher (more than 50%) in comparison to the other national programmes considered.

The only exception to the 'flat rate' scheme is reported in India, where the national biogas programme stipulates different subsidy levels depending on the size of the biodigester. The most recent version of the programme includes only two size ranges for domestic biodigesters (1-2m^3 and 2-4m^3 [39]), although the former version (as noted by Bath et al.) included a wider range of digester sizes. Bath et al. claim that this type of graded scheme may incentivise the installation of oversized biogas plants, as the cost to be covered by the household (after deducting the subsidy) does not vary much between some size ranges. This theory seems to have been borne out in Sirsi, Karnataka state, where "the biogas plants actually built are larger by an extra capacity of nearly 4 m^3 than the required size". [16]

4.5.3 Sources of credit

Another frequent claim in the studies is that potential users find it difficult to meet the remaining investment cost, even after subtracting the available subsidies. Consequently, in addition to subsidies, rural households often require loans to cover the initial investment. Most of the national biogas programmes considered include specific credit mechanisms to meet this need. In general terms, financial resources for biogas credit lines are part of a programme's budget, although the individual loans are ultimately provided by specified third party organisations. For instance, local micro finance institutes in Nepal [41]and local banks in Cambodia [48] and in Rwanda [50].

China seems to be an exception. In the six studies in China, there is no mention of loan schemes for domestic biogas investment. There may be two reasons for this. Firstly, rural households participating in the biogas programme seem to have the ability to cover the remaining costs (around half the total investment). As observed by He et al. in their sample, "no household built its bio-digester through a loan from a bank" [35]. Secondly, commercial loans in rural China are somewhat limited, which may be excluding the poorest households from the programme [36].

4.5.4 Financing actors

In a similar way to the promotion subsystem, the interplay between different organisations is central to ensuring the financial capacity of potential domestic biogas users. These organisations can be divided into six classes: state entities, international development agencies, local banks and microfinance institutions, locally-active non-governmental organisations, farmers' associations and private companies. The allocation of the overall financial resources for subsidies and credit is often assumed by central state entities, as in the case of the biogas programmes in India and China, or by a partnership between state entities (e.g. ministries) and international development agencies, as in the numerous biogas programmes where the involvement of SNV is reported (Bangladesh, Cambodia, Nepal, Rwanda and Vietnam). The actual delivery of financial support to single households is undertaken by organisations local to the rural population, such as local banks and NGOs. Consequently, the implementation of financial mechanisms (subsidies and credit) relies on institutional arrangements to funnel financial resources from central coordination agencies to more localised organisations. This may comprise several stages, in a similar way to the organisation of promotional and educational tasks as described in section 4.4. In some cases, additional financial support comes from other entities beyond the centrally-coordinated national programmes. Farmers' associations can also play a role in supporting the financial capacity of users. [16,47]

4.6 Technology supply

The adoption of domestic biogas necessitates the installation of all the physical components that make up the system (e.g. the biodigester, pipes and biogas stove). Under the label 'technology supply' we include empirical observations about how to ensure that all the required material components and skills are available to provide the technology to interested households. Factors influencing the effective supply of the technology can be divided into four categories: *training for suppliers*, *quality control*, *after-sales service* and the *actors* involved.

4.6.1 Training for suppliers

Qualification programmes aimed at building technical skills for the construction and maintenance of domestic biogas plants are in place in most of the countries covered by the reviewed studies. Often those programmes are also linked to the certification of technicians. Different observations provide evidence of the importance of training suppliers. Probably the clearest statement is given by Buysman and Mol, who assert that "training and certifying masons" is one of the measures applied by the Cambodian biogas programme in order to "build trust in biogas technology among potential clients" [48].

4.6.2 Quality control

Strategies for ensuring the quality of the plants rely on three main components.

i) Setting technical standards, which are also related to the allocation of subsidies, as illustrated by the Bangladeshi programme where the assignation of the investment subsidy to the biogas user is dependent on the fulfilment of "the specifications and standards set by IDCOL/SNV/KfW", the organisations involved in the financial coordination of the programme [32].
ii) Establishment of a supervision mechanism, which includes the physical inspection of installed plants by third parties (i.e. unrelated to the supplier and the user). This could even include "frequent random inspections of biogas plants under construction", as in the Cambodian case [48].
iii) Establishment of a certification system for technicians. This component is directly related to the training of suppliers, as described above.

4.6.3 After-sales service

The provision of post-installation technical support to users seems to be crucial to ensure the sustained use of the technology. Some national programmes include compulsory guarantees and technical support from the suppliers. For instance, in Cambodia, "a compulsory 2-year guarantee" is in place [48] and Martí-Herrero et al. recommend that technicians monitor installed digesters "until the user understands the system and its maintenance (usually 6 months)", based on the experience of the Bolivian case [47]. While setting provisions for guarantees could be a step towards ensuring sustained use, Raha et al. provide an illustration showing that the enforcement of the provisions might not take place. They found that, "although it was evident that the units had four-year guarantees, neither the village contact, nor the private contractor had visited the household post-installation to assess or monitor the plant." [39]

4.6.4 Actors involved

Different terms are used to refer to those who ultimately provide the products and services to households interested in installing or already using domestic biogas plants: 'technicians' [19,47], 'builders' [16], 'skilled masons' [32,50] and biogas 'companies' [35,48,50]. The roles of suppliers are diverse; they may look for and assess potential households, construct and install digesters and provide after-sales service and guarantees. A common expectation evident in most of the studies is that the supply and installation is undertaken by private actors who offer their products and services on a regulated market, in order to ensure the quality of the equipment and the enforcement of guarantees.

The central task of a national biogas programme is, therefore, the establishment of training and certification systems in order to create (or induce the formation) of a private sector with capacities and skills in domestic biogas technology. This also implies regulatory functions (e.g. setting standards and establishing supervision and certification mechanisms) which are assumed by the central coordination agencies, for instance IDCOL in Bangladesh, the MNRE in India and the national biogas programme offices in Cambodia and Rwanda. Putting the regulations into operation can require complex structures to transmit responsibilities from central governmental agencies to local offices. In China, this process starts in a division of the Ministry of Agriculture and ends up at local Rural Energy Offices. Of particular interest is the monitoring included in the Indian programme, which entails physical inspections from three different entities at state level, each of them reporting to the MNRE "separately for triangulation of information from the field" [39]. In less populated countries, such as Rwanda and Bolivia, partnerships with existing capacities (i.e. technical colleges and universities) have been sought for the quality control operation [47,50].

Similar patterns can be seen for the qualification of technicians. In China, this role also comes under the institutional structures of the Ministry of Agriculture [49]. In India, "training and education is delivered by the Biogas Development and Training Centres". [39] Ten such centres were in place by 2011 [52]. In Rwanda, once again a partnership was sought which involved integrating biogas qualifications into the curriculums of existing educational institutions [50].

5 Discussion

The results of our analysis illustrate the variety of ways in which domestic biogas interacts with and can potentially reshape the user's livelihood subsystems. The proposed system perspective implies that a household's ability to draw benefits from domestic biogas technology depends on the extent to which the technology is integrated into the functionality of those subsystems. This perspective highlights the many impacts that the introduction of domestic biogas technology can make. The provision of energy for cooking is by no means the only function met by the technology. Our review points to important benefits that can be achieved in a user's crop production and animal husbandry practices, as well as sanitation aspects. Moreover, a household might not perceive the impacts of biogas installation on its energy situation as the most important. The fertilising and plant protection effects of effluents might address more pressing needs of rural households, as illustrated by the study in Bolivia [47]. The effective reduction of environmental burdens associated with animal husbandry might be a stronger motivation for users, as in the case of Vietnam [46]. The installation of a biogas plant might be linked to broader improvements to a user's house (kitchen, toilet) and farm (pigpen, orchard) and appreciated for these reasons, as observed in China [37]. Additionally, from a techno-economic perspective the reviewed literature highlights the fact that the financial effects deriving from fuel substitution (the main outcome related to energy issues) are negligible if most of the energy for cooking was previously generated by non-commercial fuels, as is often the case for households targeted by domestic biogas programmes.

5.1 Acknowledging the multi-functionality of domestic biogas

Our findings suggest that the common perception of biogas as an intervention to address domestic energy needs (specifically energy for cooking) should be, at the very least, reconsidered. In examining the selected literature, it is interesting to note that only one study was published in a journal without the word 'energy' in its name, i.e. the study by Thu et al., which focuses on the impact of domestic biogas on the manure management practices of farmers in Vietnam [46]. This might point to a particular bias from our end. Indeed, understanding domestic biogas plants in terms of energy intervention is an underlying initial assumption of the present study. This bias towards energy does, however, seem to be a generalised perception. First, the term 'energy' was not used as a search criterion at any stage of the literature selection. Second, the two most central criteria for the selection process were: i) the geographical scope of the studies (case studies in developing countries) and ii) the object of the research (analyses of real experiences in the promotion and dissemination of the technology).

The emerging issue is that accelerating the diffusion of domestic biogas has been firmly linked to global discussions/discourses on energy poverty and visions of universal access to 'modern', 'clean' or 'sustainable' energy. In the standard literature on energy access, biogas is regarded as a type of 'modern' energy [1,53]. It is considered in the same set of options for modern cooking energy as LPG and electricity. While the potential benefits of effluents are recognised by all the national biogas programmes in the reviewed studies, information on the actual application of the effluent by biogas users is lacking in the majority of the studies. In some cases, the effluents are not being used at all and some of the studies highlighted a lack of knowledge about their potential use for the particular crops and practices of the targeted households. The issue of sanitation is even more marginal. Moreover, information on technical options or strategies for the integration of the technology into households' farms is scarce. The only noteworthy exceptions are the standardised packages popular in China, such as the so-called 'three-in-one' model which explicitly addresses the linkages of the technology to other subsystems beyond cooking.

Linking domestic biogas technology to the broader aim of recognising the role of family farms and strengthening their capacities would probably better fit the multi-functional nature of the technology. The essential characteristic of family farms is their reliance on family labour in managing the farm operation. The concept unifies the 'domestic' practices (at home, non-productive, non-tradable) and the 'farming' activities (on the farm, productive, tradable). "The family and the farm are linked, coevolve and combine economic, environmental, reproductive, social and cultural functions". [54] Framing domestic biogas as an option for reshaping family farms recognises the multiple ways in which the technology can influence a household's livelihood. Cooking meals is still one domain that might experience changes due to the adoption of the technology. However, it should not necessarily represent the central aim of programmes promoting the diffusion of domestic biogas, nor be considered as the strongest motivation for users to adopt the technology.

Some precautionary reflections should be added to this call for broadening the understanding of domestic biogas technologies. Recognising the multiplicity of benefits that can derive from the introduction of domestic biogas in family farms does not imply that the technology will provide a 'silver bullet solution' to the multiple challenges they face, nor that any single intervention can address all aspects of a household's livelihood. More accurately, the broader understanding of the technology suggests the need for programme designs that are more sensitive to the conditions and expectations of those family farmers targeted. In addition, the potential of domestic biogas might, in some cases, be better realised if its diffusion is considered as a tool instead of the central goal of a programme, as observed by Martí-Herrero et al. when reflecting on their experiences coordinating domestic biogas dissemination in Bolivia: "[Domestic biogas] transforms into a tool that can be integrated into many different projects such as waste and watershed management, ecology, energy, organic food sovereignty, health, climate change mitigation and adaptation, etc."[47]

5.2 The socio-technical structuration of domestic biogas

Organising the evidence according to the system perspective allows for a more in-depth explanation of the socio-technical structuration of the adoption and diffusion processes of domestic biogas. Adoption can be understood as the process in which adjustments or changes are undertaken, validated and – in the best case scenarios – routinised by the user to achieve the integration of the technology into the family farm. Diffusion comprises similar stages (i.e. change, validation and routinisation), but includes a number of agents in the process, i.e. other households and organisations. Both processes (adoption and diffusion) are closely related and it is difficult to consider one without the other, but there is an important distinction. This distinction points to *agency* and *power*, i.e. to the capability to 'act otherwise' and to mobilise resources in order to cope with the transformational challenge of integrating the new technology into the individual family farm (adoption) and into the population of family farmers in a geographical or administrative area (diffusion).

The introduction of a biogas plant into a household challenges the daily routine of the family farm operation. Once the biogas plant is installed, rules that were previously applied in a range of contexts, providing meaningful procedures for specific situations, could result in unsatisfactory outcomes. Material, normative and cognitive elements involved in routine actions or procedures could become incompatible with the actions/procedures required for domestic biogas operation. This transformative challenge at household level can be illustrated by considering the animal husbandry domain. Previous animal husbandry practices and corresponding manure management could hinder the proper feeding of the digester. These previous practices were made possible by material components (e.g. number of animals, configuration of stables and availability of water) and normative elements (e.g. rules for the allocation of labour within the household, value ascribed to manure and regulations on manure management). In order to reap the benefit from the biogas plant, the user has to adjust the animal husbandry practices accordingly. This might involve, for instance, the construction of new animal stalls or the modification of existing ones, as well as changes in the daily routine and labour allocation for husbandry practices and manure management. The grade of difficulty of the necessary transformative tasks depends on (i) how compatible the structures that framed the previous practices are with the new configuration required for the domestic biogas plant and (ii) the ability of the user to access resources needed for the transformation; for instance financial capital (e.g. for modifying stables), knowledge (e.g. about adequate water use and cleaning practices) and technical skills (e.g. for design and installation of auxiliary devices adapted to the specific farm configuration to facilitate the feeding of the biodigester). This transformative capacity of the individual household highlights the linkages between individual adoption and wider diffusion of the technology.

The transformative capacity of domestic biogas users is likely to be low, given the novelty of the technology, the users' lack of finance and the general marginalisation of family farmers [54]. Crucial resources for achieving the integration of the new technology at household level are beyond the control of individual users. Facilitating access to those resources is the central task of programmes aimed at disseminating domestic biogas. This role involves the deployment of power in the sense proposed by Giddens in his description of structuration theory. He distinguishes two sorts of resources in the structuration of power: "authoritative resources, which derive from the co-ordination of the activity of human agents, and allocative resources, which stem from control of material products or of aspects of the material world."[55] Sections 4.5 to 4.7 illustrate how allocative and authoritative resources are deployed by national biogas programmes in an attempt to complement individual farmers' lack of resources. Different institutional configurations have been established in order to increase the transformative capacity of households and ultimately empower family farmers. Common features of these programmes are a predominantly 'top-down' flow of resources, as well as a hierarchical organisational structure stemming from a central coordinating agency (commonly a state organisation) towards organisations whose range of actions are closer to the local farmers. Programme funding is provided from national budgets as well as from international development agencies or banks. Standards and procedures are established in order to organise the further allocation of funds. At this stage not only are subsidy schemes defined, but other relevant nationwide issues such as promotional strategies, training programmes, quality standards and monitoring procedures are established.

The scope of national biogas programmes covers – as the name suggests – rural populations in different geographical and administrative regions. The aggregated volume of resources requiring allocation and the coordination effort needed to ensure their effective distribution and application would be difficult to organise in a 'bottom-up' or 'horizontal' structure. However, the reviewed literature offers interesting indications about the contribution that more decentralised or localised capacities and 'horizontal' flows could bring to the diffusion process, even when it is framed within a large national geographical scope. Locally-active NGOs have been working on domestic biogas application and accumulating context-specific knowledge for decades, as shown in the studies in Bangladesh, Tanzania and Uganda [32,44,45]. Local farmers' associations can be involved in the diffusion of the technology by providing information and financial resources to users, as illustrated by the studies in India and Bolivia [16,47]. The flow of information between farmers has been identified as a significant factor for motivating new users, as reported in studies in Bangladesh, Cambodia, Rwanda and Vietnam [32,46,48,50]. It is becoming clear that significant transformative capacities can be found at more localised levels. While these local organisations are unlikely to be able to drive national diffusion processes, their resources (knowledge, coordination abilities, communication channels with the local population, financial instruments etc.) could be suitable for adaptation to the local context and circumstances of the family farmers with whom they commonly interact. Ensuring the integration of existing local capacities into national biogas programmes could increase the sustainable adoption of domestic biogas technology by family farms and increase the range of benefits gained.

6 Conclusions

The present study systematically organised available evidence of the factors that influence the adoption and diffusion of domestic biogas in developing and emerging countries. To achieve this aim, adoption and diffusion were conceptualised as the processes by which the dynamic systems that frame the livelihoods of potential users adjust once the new technology is introduced. Organised in this fashion, the evidence reported by scientific studies indicates that:

i) the adoption of domestic biogas creates a particular challenge for the functionality of three subsystems configuring households' farms: cooking, animal husbandry and crop production;
ii) the adoption and diffusion processes are both determined by the ability of users to access resources beyond their own households, in particular knowledge (about the technology and its potential benefits), financial capital (for the required investments) and skilled suppliers (providing the corresponding products and services); and
iii) the successful diffusion of domestic biogas in a given social system (i.e. achieving a situation where the greatest number of potential adopters are using the technology in a sustained way) is determined by the compatibility between the functionality of the new technology and the mentioned subsystems.

The factors that regulate the interactions between domestic biogas and the outlined subsystems are summarised and schematically displayed in Figure 2. The analysis suggests that in practice domestic biogas technology is mainly considered as a tool for addressing domestic energy needs, in particular energy for cooking. However, our results also underline the multi-functionality of domestic biogas. We therefore recommend linking domestic biogas technology to broader attempts to recognise and strengthen family farms. We argue that in this way the potential benefits deriving from the technology's multi-functionality will be better appreciated by family farmers and the benefits will, consequently, meet their actual needs.

In addition, our analysis advances the understanding of the socio-technical structuration of the adoption and diffusion of domestic biogas technologies. In this regard the analysis emphasises that crucial resources (e.g. knowledge, finance and skills) for achieving the broad diffusion and sustained use of domestic biogas are beyond the control of individual households. The results show that the common response to this fact is the establishment of programmes organised in a 'top-down' structure. However, we also found evidence of the availability of resources and significant capacities at more localised levels, such as locally-active NGOs, experienced practitioners and farmers' associations. Their resources and capacities could be particularly suitable for adaptation to the local context and circumstances of the family farmers they serve. Ensuring the integration of these local capacities into national programmes could improve the outlook for the successful and sustainable diffusion of domestic biogas.

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Captions

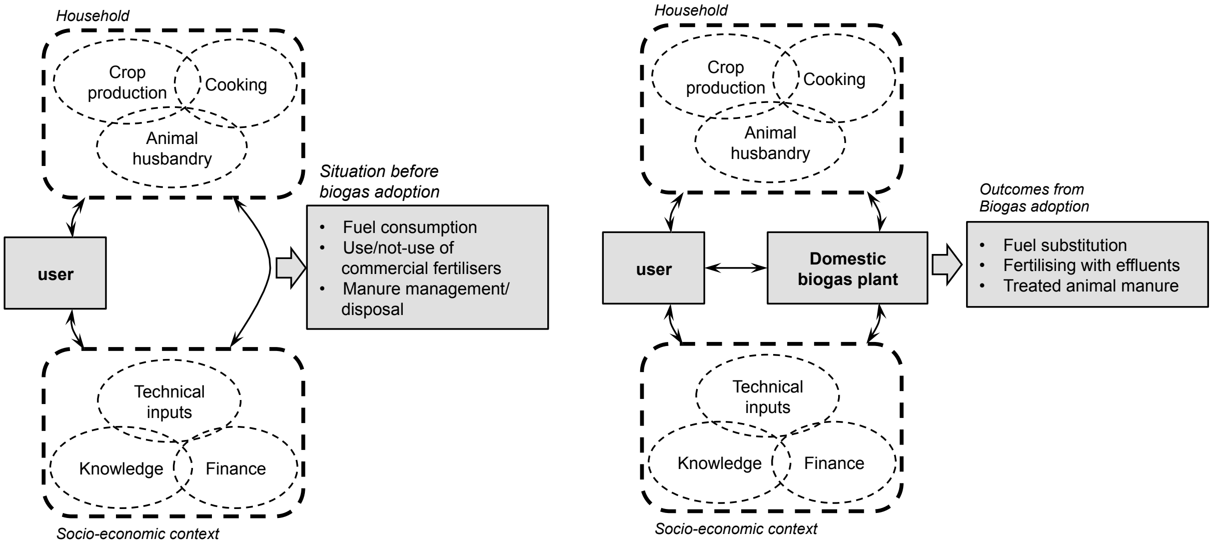

Figure 1 Schematic description of the conceptual model proposed to understand the dynamic processes triggered by the introduction of a domestic biogas plant into an individual household.

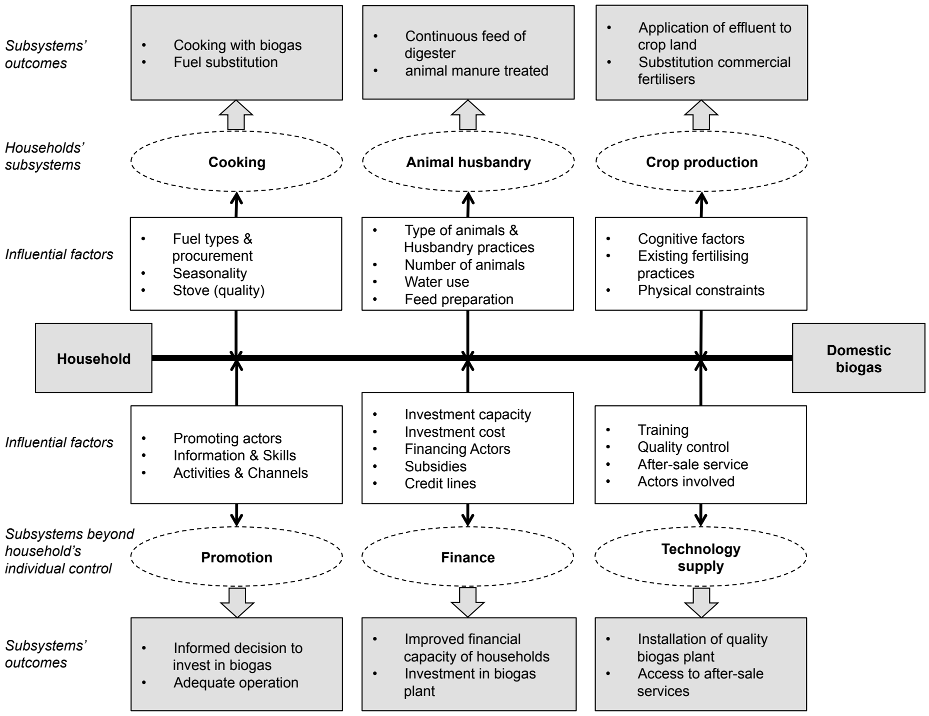

Figure 2 Schematic view of a system perspective of domestic biogas adoption and dissemination. The ability of a household to draw positive outcomes from domestic biogas technology is influenced by the extent to which the technology is integrated into (matches) the functionality of a household's livelihood subsystems, which in turn are affected by the presence of the technology. Factors influencing this integration process are listed (rectangles in white). The graphic presents a hypothetical situation of successful integration in all subsystems and the corresponding outcomes (shadowed rectangles).