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Rethinking socio-cultural resistance: Systemic factors behind successful and failed transitions to toilet-linked anaerobic digesters in Nepal and India

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ABSTRACT

Toilet-linked anaerobic digesters (TLADs) are promoted as technologies that can simultaneously address household energy, sanitation, and agricultural needs, yet diffusion remains uneven, and project failures are frequently attributed to "socio-cultural resistance." This paper challenges that narrative by examining why Nepal's domestic biogas programme achieved greater success in implementing TLADs than India's, despite broadly similar policies and rural socio-economic conditions. Using a sustainability transitions framework, we conduct a comparative case study of successful adoption in Nepal's Gandaki Province with non-adoption in Assam, India. The study draws on 57 household interviews, 15 expert-stakeholder interviews, and policy and programme documents. Findings indicate that while socio-cultural norms influence TLAD diffusion, they are not stand-alone determinants of household transitions. Instead, these norms interact with programme design, governance structures, institutional commitment, and wider policy environments, and are conditioned by local socio-technical contexts. These interactions shape how socio-cultural norms manifest in relation to technology adoption at the household level. We argue that failed transitions are too often attributed disproportionately to socio-cultural resistance—a framing that unfairly shifts responsibility onto households while obscuring systemic shortcomings such as inadequate targeting, weak institutional support, and misalignment between technologies and local contexts. A more balanced framing should acknowledge socio-cultural norms while situating them within broader socio-technical and policy environments. Such reframing could shift research and practice away from narratives of household blame and towards critical assessments of contextual fit, programme capacity, and policy coherence, supporting more equitable and context-appropriate transitions in sanitation and household energy systems such as TLADs.

1. Introduction

Domestic biogas is a decentralised energy solution where households both produce and consume energy directly on-site [1,2]. The potential autonomy offered by biogas can provide households flexibility without reliance on traditional wood fuels or fuels like liquid petroleum gas (LPG), potentially improving affordability and supply security issues. Biogas is a cleaner fuel than wood fuel reducing respiratory and eye health issues associated with its combustion and can alleviate the burden of firewood collection, often done by women and children, while decreasing fuel costs. When integrated with latrines to create a toilet-linked anaerobic digester (TLAD), biogas systems can improve household sanitation [2,3]. The byproduct of the digestion process, bio-slurry, can be an effective plant fertiliser, enhancing agricultural productivity, soil health, and reducing dependency on chemical fertilisers [4].

For domestic biogas technology and its products, biogas and slurry, to effectively replace existing cooking, agriculture, and sanitation solutions within local socio-technical regimes[1] more than a simple reactor is required. A successful household transition to biogas technology involves significant changes across multiple dimensions: cultural, economic, technological, and political [6]. For the transition to succeed, households or communities must adopt new cooking and fertiliser products and practices, integrate them into daily routines, and develop

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[1] Socio-technical regimes refer to established systems or 'ways of doing things' that encompass policies, markets, infrastructures, and user behaviours that have co-evolved with resources, technologies, and institutions over time [5,6]

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new knowledge systems. For example, wood fuel is often used for both cooking and space heating, and its use is rooted in long-standing traditions, flavour preferences, and skills passed down through generations [7,8]. The use of fuel wood is supported by established local supply chains and, for some, provides an income through collection and sale. Transitioning to biogas as a new cooking fuel demands a substantial shift away from socio-cultural norms. This shift potentially involves renegotiating socio-cultural norms, reconfiguring economic incentives, developing supportive policies, and creating new market structures. Achieving sustained household transitions to biogas, where biogas becomes integrated into local socio-technical regimes, will necessitate changes across all these dimensions. Taken together, these points show that household transitions to biogas depend not only on individual choices but also on the wider socio-technical context, including policies, markets, and supply chains.

Domestic biogas technology is well suited to many rural South Asian contexts, including parts of Nepal and India. The warm climate, large rural populations, and widespread reliance on agriculture and livestock make these areas especially appropriate for biogas installation [2,9]. Furthermore, in many regions of both countries, there is a tradition of rearing cows and buffalos, whose dung is commonly used as biogas feedstock [10,11]. Importantly, livestock are often kept close to the home, providing an accessible supply of dung that can be collected for feeding the biogas digester. Both countries have national biogas programmes and have been promoting and subsidising biogas installations with and without toilet connections since the 1980s. As of 2019, Nepal has installed approximately half a million domestic biogas digesters [12,13] and in India it is estimated that to date, around 5 million have been installed [14]. Both countries offer additional subsidies to encourage households to construct TLADs, promoting the use of household excreta as a feedstock alongside cattle dung to enhance the waste management and sanitary benefits households can achieve from biogas technology [15–18].

Nepal and India are neighbouring countries that share complex histories and demographics. At a very high level they also share some rural socio-economic characteristics. Both countries have predominantly Hindu populations, where historically entrenched caste-based social stratification, shaped by notions of ritual purity and linked to traditional occupations, continues to influence everyday life despite formal legal prohibitions on caste discrimination [19]. Sanitation work, which is ritually, as well as physically polluting, has been typically forced upon people of lower castes from whom higher castes segregate themselves [19]. Through exposure to a ritual state of pollution, such as using human excreta derived biogas, householders can experience negative socio-political consequences, such as no longer receiving visitors after adopting a TLAD [20]. In Hindu contexts, households from higher castes often hold elevated social status irrespective of income, although they are also more likely to hold higher-paying professions. This status can influence their access to resources such as energy, land, and water. The adoption of a TLAD could affect a household's social status, potentially reshaping these access dynamics [21]. In Hindu village life, religion can cascade into practical life [22] where ritual practices have co-evolved within specific socio-ecological contexts and may oppose the adoption of TLADs. Cooking with wood fuel is linked to ritual purity and connects users with traditional cultural cooking practices but it also connects households to their socio-ecological systems, providing space heating and resources such as ash that is used as a detergent and pesticide and is a means of disposing of waste [7,20,23].

The two nations' biogas programmes share similar policies and governance structures but have experienced varying outcomes. Nepal's programme is often regarded as a historical success, with reports of high post-installation functionality rates [13,17,18]; however, its effectiveness appears to be declining over time. To date, less than 1 % of Nepal's total biogas potential has been realised, despite decades of government support and international financing [24]. India has achieved success in installing 5 million digesters but is marred with reports of poor functionality rates post-installation that have been as low as 40 % in some studies [25,26]. Both countries offer additional subsidies for toilet connections. Interestingly, in some areas of Nepal, an estimated 80 % of domestic biogas users have connected their household toilets to biogas digesters [17], whereas in India, toilet connections remain very limited; a situation often attributed to opposing socio-cultural norms [27–30]. These differences highlight the complexities in evaluating programme outcomes, as data gaps and contextual variations make it difficult to fully assess the successes and challenges of each approach. Given the suitability of biogas technology to certain rural regions in both Nepal and India, and the shared socio-cultural beliefs around purity, pollution, and sanitation in parts of these countries, what factors have contributed to the comparatively higher uptake of TLAD systems in Nepal?

The purpose of this study is to investigate why Nepal's domestic biogas programme has outperformed India's in disseminating TLADs in some local socio-technical regimes, despite similar national programme policies and overarching rural socio-economic demographics. Using localised case studies in Nepal and India, informed by household interviews and expert stakeholder insights, the study compares the two countries' domestic biogas programmes at both the national scale and in the local case study sites. Framed within sustainability transitions literature, the study aims to understand why TLADs might penetrate some socio-technical regimes but not others, considering the broader policy, governance, and socio-technical contexts as well as household decision making and cultural norms. This approach not only investigates local factors such as alternative energy products, market dynamics, and governance structures, but also integrates an analysis of national-level policies, institutional frameworks, and decision-making processes. Recognising that both countries' biogas programmes operate nationally but are implemented by local institutions, the study's dual-level analysis seeks to provide a more comprehensive understanding of why TLAD transitions succeed in one context and not another.

2. Literature review

2.1. Understandings of success and failure within domestic biogas programmes

Due to its many potential benefits, biogas has often been heralded as a silver bullet solution to many sustainability challenges. It has been implemented as a top-down, technological fix to complex rural challenges in low- and middle-income countries for decades [2,3,18,31]. Initially, in response to the oil crises of the 1970–90s, biogas technology was promoted in Nepal and India for its capacity to make farming and household energy needs independent of fossil fuels, aiming to support rural development as well as reduce deforestation [25,32]. Later, the emphasis on biogas shifted towards mitigating diseases from indoor air pollution and poor sanitation, and empowering women by lessening the burden of firewood collection. By the 2000s, domestic biogas globally had become framed as a strategy against climate change, with a shift towards a more neoliberal and market-driven approach, recognising its revenue potential within global carbon markets [32–34]. Since the 1970s domestic biogas has garnered significant investment from governments, international organisations, NGOs, and households across Africa, Asia, and South America.

Despite its potential, the story of domestic biogas has been fraught with failure [35,36]. For instance, by the end of 2015, the number of China's installed household biogas digesters under their national biogas programme reached 41.9 million, but it has been estimated that only 40–60 % of these were being utilised post installation [37]. In India, of the approximately 5 million installed as part of the national programme it is estimated that post installation functionality is between 40 and 80 % [26,30]. A study of the Africa Biogas Partnership Program which commenced in 2009 in Tanzania, Uganda and Kenya found 27 % of sampled biodigesters inoperative as of 2016 [38].

Despite these widespread failures, literature to date has largely focused on identifying common barriers to uptake, such as those summarised in Table 1. However, as Boyd Williams, Kalina and Tilley [39] argue, these barriers are so widespread and repeatedly encountered that they could be better understood as *symptoms* rather than root causes of failure. As Boyd Williams et al. [40] demonstrate in their examination of a UNDP-funded biogas project in Malawi, post-project evaluations by stakeholders cited familiar barriers such as inadequate training and maintenance services, as well as the selection of beneficiaries without sufficient feedstock. A closer analysis, however, revealed deeper systemic flaws: digesters had been hastily installed in remote areas just before funding expired, amid suspected corruption and a widespread lack of biogas expertise among stakeholders. The project failed not because of the 'common barriers' often cited in the literature, but due to weak leadership, poor governance, and a fundamental lack of understanding of the local context and the requirements for successful implementation. We contend that overall, research has tended to emphasise proximate symptoms of failure while neglecting deeper systemic explanations for why biogas succeeds in some localities but not others.

Some notable studies have focussed more on understanding the systemic root causes of biogas programme success and failure, demonstrating the value of this deeper perspective, though it has yet to become a research priority. A key example is Rai's [12] in-depth analysis of Nepal's national biogas programme, which traces its early successes and subsequent decline while linking programme outcomes to the broader socio-technical context. His work describes how early successes were driven by factors such as Nepal's unique pursuit of energy independence, due to its reliance on fossil fuel imports from India, as well as the programme's early approach to good governance and inclusion of grassroots actors. The programme's decline is further analysed to reveal how shifts in institutional actors and governance structures—leading to increased centralisation and regulation—played a significant role. Another example is provided by Bhat, Chanakya, and Ravindranath [26], who analysed the performance of India's national biogas programme in the local context of Sirsi, a city in Karnataka. Key localised elements to success in this case study included the involvement of local agencies like growers' associations in disseminating and financing biogas, and the region's high demand for slurry for regional agricultural activities. Supporting these studies are others that highlight how multi-sector policy mismatches, fragmented governance, overly optimistic programme reporting, and flawed programme design can negatively impact biogas programme outcomes [29,30,41–46].

Sustainability transitions research is a growing interdisciplinary field that seeks to understand and facilitate the transformation of societal systems towards more sustainable technologies and practices [58–60]. Unlike traditional disciplinary approaches, it emphasises the inherently socio-technical nature of these shifts, recognising that technological innovation and social change are deeply interconnected. Rather than treating sustainability challenges as purely technical or social, this approach examines how policies, cultural norms, market dynamics, governance, and infrastructure interact to drive or hinder the adoption and diffusion of sustainable solutions. Transitions often begin with niche innovations: experimental and unstable environments where new ideas and technologies emerge. Niches are typically protected spaces, such as subsidised demonstration projects or community initiatives, where users support emerging innovations. Over time, successful niches can influence or integrate into socio-technical regimes: the 'deep structure' of a stabilising system. Regimes are shaped by governance, production systems, markets, infrastructures, and policies, all of which collectively determine the trajectory of innovation adoption [61–64].

Table 1
Barriers to successful uptake and use of domestic biogas technology.

Barrier group	Details	References
Financial/ economical	• High upfront investment costs for households. • Delays in disbursement of subsidies or difficulty accessing credit. • Over-subsidisation reduces user ownership, leading to system neglect or abandonment. • Low portability of digesters makes them unattractive for renters or mobile households.	[4,29,30,42,43,47–57]
Market	• Limited competition among providers for construction and repair services. • Competition from alternative energy sources (e.g., LPG, solar, electricity). • Weak private sector engagement in dissemination and maintenance. • Underdeveloped markets for by-products such as surplus feedstock and digestate fertiliser.	
Socio-cultural/ behavioural	• **Resistance to using human/animal excreta as a fuel source** • Gendered divisions: men control finances while women manage cooking. • Perceptions of labour-intensiveness reduce appeal. • Cultural food preferences tied to traditional fuel (taste, heat intensity). • Social elites dominate dissemination, excluding marginalised groups. • Collecting firewood embedded in social norms and practices. • Higher social prestige associated with LPG compared to biogas.	
Regulatory	• Insufficient follow-up services (training, repair, maintenance). • Poor local availability of spare parts and skilled technicians. • Lower prioritisation compared to other rural energy initiatives. • Weak political commitment and infrastructural support.	
Technical and Infrastructural	• Inconsistent feedstock supply (animal manure, crop residues). • Limited water availability reduces digester performance. • Lower flame intensity slows cooking relative to traditional fuels. • Poor performance in cold climates; seasonal fluctuations in gas supply. • High maintenance burden and repair difficulties. • Inadequate household labour to sustain livestock management. • Digesters cannot replace other household energy needs (e.g., space heating). • Operational issues: leakage, reliability, low gas yields. • Geographic remoteness impedes installation and servicing. • Difficulties in transporting and using slurry in liquid form.	
Information/ Knowledge	• Limited user knowledge and agency to operate systems effectively. • Weak awareness campaigns on biogas benefits. • Many users unaware of entitlements to maintenance services or subsidies. • Health benefits of clean cooking undervalued or poorly communicated. • Safety concerns around biogas and digestate handling. • Low risk perception regarding traditional biomass cooking.	

A sustainability transitions approach offers significant potential to advance understanding of domestic biogas by moving beyond single-discipline perspectives, single-level analyses, and narrow temporal frames. A multi-level and temporal perspective could help address critical gaps in current research, particularly the tendency to focus on symptoms of failure while neglecting the broader structural and systemic factors that have evolved alongside the socio-technical backdrop. A sustainability transitions approach could help shift research attention to higher-level influences on biogas programme outcomes, such as policy and programme governance, political dynamics, and decision-making processes.

Only a small number of research studies could be found that have applied sustainability transitions theories or frameworks to explore transitions to domestic biogas. The studies applied either national programmes, as seen in the works of Tigabu, Berkhout, and van Beukering [65], Kamp and Bermúdez Forn [66], and Bößner et al. [67], or localised case studies, as applied by Campbell and Sallis [68] and Pilloni, Hamed, and Joyce [69], as units of analysis. Investigating nationwide transitions to domestic biogas through a sustainability transitions lens enabled researchers to gain high-level temporal overviews of programme development, setbacks, and interdisciplinary barriers and opportunities for biogas uptake. For example, Kamp and Bermúdez Forn [66] highlighted that interactions between actors from different government ministries influence the success or failure of programme implementation in Ethiopia. However, by focusing solely on the national scale, these studies fall short of explaining why domestic biogas succeeds or fails in specific localities within the same country. While the high-level perspective offers valuable insights into systemic challenges and dynamics, it does not capture the nuanced, context-specific factors at the local level, such as socio-cultural, economic, or governance-related differences that ultimately shape household adoption.

The studies that focused on local case studies provided a more detailed understanding of specific local socio-technical transition dynamics. However, they were limited in examining how national-level decision-making, governance, and policies shape the diffusion of biogas within these areas. None of the studies explored how the interplay between national and local socio-technical contexts—such as historical events, socio-economic demographics, and programmatic implementation—mediates outcomes. As a result, neither the national nor local approach fully captures the complex interactions between these scales. This gap highlights the need for a more integrated approach that accounts for the dynamic interactions within socio-technical systems at multiple levels.

2.2. Understanding success and failure of transitions to domestic biogas with toilet-connections

Literature specifically focusing on the successful or failed implementation of TLADs is sparse. Until recently, a common conclusion, either drawn by researchers or suggested by study participants, is that successful TLAD adoption is primarily influenced by local socio-cultural norms [29,46,70]. There are very few dedicated studies on TLADs; most research treats them as part of broader biogas investigations. As a result, resistance to human excreta as feedstock is noted as the main distinction (see Table 1 in bold). In practice, however, TLADs differ fundamentally from conventional biogas digesters. They function not only as energy and agricultural technologies but also as sanitation solutions. This means that successful transitions require penetration and stabilisation within an additional socio-technical regime—one shaped by existing sanitation technologies and social practices around excretion and disposal. This consideration is largely missing from existing literature.

In India, the low prevalence of TLADs has been attributed to widespread socio-cultural resistance towards using human excreta as feedstock [29,70], despite there being a small number of case studies where TLADs have been adopted [27,28,71]. What distinguishes these successful TLAD adoption case studies from the failed ones within India, despite the same national programme approach and policies, remains an open and unexplored question within research. In contrast, countries like Nepal, Vietnam, and China have seen more widespread adoption. In China, there is a historical use of human excreta as fertiliser [3,72] perhaps making the practice more of a social-norm but there is a lack of literature exploring why Vietnam and/or Nepal has more widely accepted TLADs, or if there are intra-country differences, like in India. Attributing TLAD success or failure solely to socio-cultural acceptance or resistance oversimplifies the issue by neglecting programmatic differences and variations in local socio-technical contexts. Such a perspective renders transitions seemingly random and obscures the ways in which governance, policy implementation, and support mechanisms actively shape outcomes.

Recent research, by Boyd Williams and colleagues [46,73], challenges the view that TLAD diffusion is primarily or solely driven by socio-cultural norms. Drawing on household interviews in Gandaki Province (formally Province 4), Nepal, and Assam, India, these studies suggest that socio-cultural norms strongly influence adoption and shape adoption pathways. However, they are likely neither the sole nor the primary determinants of successful household transitions [46,73]. The authors highlight additional factors influencing TLAD success or failure, including the availability of alternative fuels and sanitation options [46], opportunities to observe and trial a TLAD in the local area before adopting one, as well as potential users' perceived needs and motivations [46,73] which are shaped by the local context inclusive of the policy environment. For instance, households in Assam with access to affordable energy, fertiliser, and sanitation alternatives—often subsidised through other government programmes—had little incentive to renegotiate socio-cultural norms and adopt a TLAD [46]. While this might be labelled as socio-cultural resistance, it could be more accurately understood as a complex interaction of priorities and needs shaped by the policy context. Reducing failed adoption to household socio-cultural resistance risks blaming households for outcomes that are shaped by far more complex dynamics. Failed adoption may reflect a lack of attention to local contexts, weak policy support, or simply that TLADs are not suitable for the context. Although some studies note policy incoherence that affects domestic biogas uptake, for example in Bolivia where households continue to use LPG after adopting biogas because it is subsidised, widely available, and associated with higher social status, there is still little research on how policies across sectors align and how this alignment influences domestic biogas. In particular, the role of cross-sector policy integration in shaping TLAD diffusion remains a critical but largely unexplored area.

In summary, we argue that existing research does not yet explain why TLADs succeed in some socio-technical contexts while failing in others. Much of the literature focuses on the symptoms of programme failure while overlooking deeper systemic causes. TLADs, when mentioned, are often treated simply as biogas technologies, without recognising their dual role as sanitation solutions that must integrate into an additional socio-technical regime. Moreover, little research applies a socio-technical transitions perspective to household adoption, which would allow transitions to be understood as systemic shifts rather than primarily as household decisions. Where such a lens has been used, studies tend to remain confined to either the local or national scale, neglecting the dynamic interplay between the two. In response to these gaps, this study applies a sustainability transitions framework to guide both the design and analysis, enabling an examination of TLAD adoption as a complex, multi-scalar process rather than through isolated disciplinary or analytical lenses. By broadening the scope beyond household-level enablers and barriers, this approach seeks to uncover systemic root causes of programme outcomes and to bring into question the dominant narrative that household socio-cultural resistance is the primary obstacle to TLAD adoption.

3. Study sites and methodological approach

3.1. Site selection and description

This research aims to investigate why Nepal's national biogas programme has had more success implementing TLADs than India's using a case study informed approach. Two distinct cases: Gandaki Province in Nepal and Assam in India, are analysed through a cross-case comparison. In Gandaki Province, TLADs are widespread, while in Assam, TLADs are, to our knowledge, non-existent. This article builds on two earlier investigations on TLAD diffusion in Gandaki Province [73] and Assam [46]. It reutilises two household interview datasets from those studies and supplements them with a new set of interviews conducted with expert stakeholders.

Referring to Table 2 Gandaki Province is much smaller than Assam, with slightly higher average income and stronger sanitation access, yet rural households rely slightly more on solid fuels than Assam. Calculations using the data in Table 2 suggests that 16.5 % of households (24.2 % of all biogas installed in Nepal is in Gandaki Province) in Gandaki Province have or have had biogas (as there is no data on functionality). Nepal's latest Demographic and Health Survey of 2022 finds 23.5 % of rural households in Gandaki primarily rely on clean fuels and technologies for cooking which includes biogas but also electricity, LPG/natural gas, and solar [74]. Official estimates from the Ministry of New and Renewable Energy suggests that 2.2 % of households in Assam have received biogas installations. Data from the latest National Family Health Survey from 2021 estimates that 1.1 % of households in Assam use biogas for cooking [75]. Data on toilet-linked biogas digesters is limited to non-existent and highly uncertain in both localities as neither government agency releases installation data on TLADs.

The household interview datasets that form the secondary data for this study have already informed two related publications and consist exclusively of household-level interviews. In Gandaki Province, these interviews captured individual accounts of TLAD adoption, while in Assam they documented household experiences with biogas without toilet connections and perceptions of TLADs, as none of the interviewed households in Assam had one, see Table 3. These earlier studies suggested that transitions to TLADs extend beyond household decision-making and are shaped by broader socio-technical histories at village, state/provincial, and national levels. These findings underlined the need for further investigation and motivated the present study, which extends the earlier work by examining wider influences on TLAD diffusion through a sustainability transitions lens. Accordingly, we retained Gandaki Province and Assam as case study regions and re-analysed the existing household datasets alongside the expert stakeholder interviews, which constitute the primary data for this investigation.

Initial site selection for the household interviews was based on convenience sampling. Gandaki Province and Assam were chosen due to existing ties with local stakeholders and gatekeepers who facilitated household identification and access. Sampling criteria differed by country. In Nepal, households with TLADs were targeted, and rural areas outside Pokhara in Gandaki Province were selected because gatekeepers could identify locations where TLADs were present and sites were relatively easy to reach in the hilly region of Nepal. In India, the case study focused on an area where households had not yet transitioned to TLADs and that was geographically close to Nepal (compared to many states of India). Assam was selected not only because of proximity to Nepal and research partnerships facilitated household access, but also because it provided an interesting comparison, with many households being of Nepali descent due to historical migration. Some households interviewed in Assam had visited relatives in Nepal with TLADs. A more detailed explanation of sampling methodologies can be found in the original publications [46,73]. A map of the study areas can be found in Fig. 1.

3.2. Methodology

Given the exploratory nature of the study, we employed a qualitative

Table 2

Comparison of Gandaki Province (Nepal) and the State of Assam (India) on household indicators, and on biogas and TLAD diffusion. The wording of indicators differs between comparisons to reflect the original phrasing in the data sources.

Indicator	Gandaki Province (Nepal)	Assam (India)
Average per-capita income (USD)	Average per-capita income (USD) Nepal $1447 for 2024 [76]. Average per-capita income (USD) Gandaki $1619 for the fiscal year 2024–25 preliminary estimate [77].	Average per-capita income (USD) India $2697 in 2024 [78]. Average per-capita income (USD) Assam ₹118,504 ≈ $1508 (2023) [79].
Number of households	Approximately 662,480 households in the Gandaki Province in 2023 [80].	Approximately 6.4 million households in Assam [81].
Households using clean fuels for cooking	Rural households in Nepal that are mainly using clean fuels and technologies for cooking in 2022 = 21.2 % [74]. Rural households in Gandaki Province that are mainly using clean fuels and technologies for cooking in 2022 = 23.5 % [74].	Rural households in India that are using clean fuels for cooking in 2019–2021 43.2 % [82]. Rural households in Assam that are using clean fuels for cooking in 2019–2021 33.7 % [75].
Households using solid fuels for cooking	Rural households in Nepal that are mainly using solid fuels for cooking in 2022 = 78.6 % [74]. Rural households in Gandaki Province that are mainly solid fuels for cooking in 2022 = 76.5 % [74].	Rural households in India that are using solid fuels for cooking in 2019–2021 = 56.1 % [82]. Rural households in Assam that are using solid fuels for cooking in 2019–2021 = 65.1 % [75].
Households with improved sanitation access	Rural households in Nepal with an improved sanitation facility in 2022 = 90.5 % [74]. Rural households in Gandaki with at least basic service (Defined as use of improved facilities that are not shared with other households. Includes safely managed sanitation service) in 2022 = 79.8 % [74].	Rural households in India with an improved, not shared sanitation facility in 2019–2021 = 63.6 % [82]. Rural households in Assam with an improved, not shared sanitation facility in 2019–2021 = 67.3 % [75].
Households using biogas for cooking	Estimated (cumulative) total household biogas installations in Nepal to date through the national biogas programme = 450,770 as of 2023/2024 [83]. Estimated country wide potential = 1.9 million [18]. Gandaki Province has approximately 24.2 % of all biogas installed in Nepal within the Province (Province with the second highest installation rate) [84].	Estimated (cumulative) total household biogas installations in India as of 2021 to date through the national biogas programme = 5 million [14]. Estimated country wide potential = 12 million [85]. Estimated (cumulative) total household biogas installations in Assam as of 2021 to date through the national biogas programme = 138,483 [14,86] (approximately 2.2 % of Assam's 6.4 million households [81].
Households using toilet-linked anaerobic digesters	The Government of Nepal (AEPC) does not publicly report how many biogas installations have toilets connected. A 2017–2018 survey sampling 135 households across Nepal found that 79 % of households had a toilet connected to a household biogas digester [17].	The Government of India (MNRE) does not publicly report how many biogas installations have toilets connected. The MNRE sets annual targets for toilet connections. For 2024–25, Assam's target was 50 TLAD installations. Public reporting on annual target achievement is unavailable [87].

Table 3
Summary and description of stakeholders and households interviewed with identifiable information removed.

Actor	Number of participants	Description	Participant number
Government association	Nepal – 1	Participant had experience working with or for a government organisation that has participated in the biogas programme	1
Researchers	Nepal – 2 India – 3	Participants had experience researching domestic biogas as well as other clean cooking programmes and wider developmental projects	3,5,2,4,6
Works for NGO/ International government organisations, private companies	Nepal – 6 India – 3	Participants worked for international NGOs, international government organisations or private companies such as private biogas installation companies and or carbon credit schemes that build biogas to offset emissions	7,9,11,13,15,17,8,10,12
Users or potential users of biogas	Nepal – 17 user participants India – 40 user participants	Gandaki Province- All participants had toilet-connected biogas (functioning or non-functioning). A full explanation of study area can be found in [73]. Assam - 25 participants had dung-fed digesters (no toilet-connections) (functioning or non-functioning) and 15 had no biogas digesters A full explanation of study area can be found in [46].	U1 – U17 U18-U58

case-study design. The primary dataset comprised 15 expert-stakeholder interviews, complemented by a secondary dataset of 57 household interviews across the two research sites (see Table 3).

The 15 expert stakeholders were interviewed online or over the phone between September 2020–January 2022. In total, 24 expert stakeholders were approached for an interview and 15 agreed to participate. Eligibility required experience working on or researching domestic biogas implementation in either study country, or related research; no currently serving Indian government officials were available for interview. A summary of the expert stakeholders included in the study can be found in Table 3. Semi-structured interviews were conducted and transcribed in English and the standardised interview guides can be found in Supplementary Materials (interviews were adapted depending on the participant). The interviews examined programme implementation and probed causal relationships among policy coherence, programme design, and contextual factors at national and local scales. The format also allowed open-ended discussion of household transitions to TLADs at both national and local levels, opening up discussion beyond the specific case study regions. To mitigate subjectivity and situate the results within a longer-term socio-technical context, we triangulated interview insights with a targeted literature review guided by interview-emergent themes. In the Finding section, cited sources are used to corroborate and contextualise the interview results rather than as a standalone dataset. While not novel findings in themselves, the included sources reflect stakeholder-driven insights and are reported where they substantiate themes raised by participants.

The 57 household interviews were conducted between August 2019 to July 2020 [46,73]. A description of the study participants are presented in Table 3. Household interviews were conducted in villages in the Gandaki Province and Assam, in local languages and transcribed into English. In Nepal (all households had TLADs), we examined experiences with domestic biogas, use of TLAD products, and the duration/process of the transition. In Assam (no households had TLADs), we explored adoption intentions, potential motivators, and perceived reasons for non-adoption. The interview guides can be found in Supplementary Materials.

All identifiable information about the stakeholders and households has been removed from the results. Each interview was recorded and transcribed with the written permission of all participants and ethical approval was obtained from the University of Stirling. Interview data were analysed through thematic analysis (TA) using NVivo 12 software. TA was employed due the method's structured yet adaptable nature. Braun and Clarke's (2006) [88] phases of TA were followed through an inductive and then deductive coding method. The deductive coding was guided by sustainability transitions literature and theory.

Data collection and analysis proceeded in staged, iterative cycles (September 2019–January 2022), reflecting cumulative learning. The study began at the household level and yielded two independent publications ([46,73]). While informative, those studies suggested that adoption outcomes are shaped by programme design and longer-term socio-technical dynamics. Accordingly, we applied a sustainability transitions lens and extended the analysis to include expert stakeholders. We examined national and local implementation histories, supported by an in-depth literature review guided by this framework and by insights from interviews. This sequential adaptation explains the extended timeline of this study and the shift from micro- to macro-level analysis. Assembling additional user-level datasets was not feasible and so the contribution is a theory-informed comparative case study: household evidence motivates the inquiry, and stakeholder testimony and documentary sources corroborate and contextualise the cross-case study and country comparison.

The expert-stakeholder sample is small ($n = 15$). However, many participants were directly involved in designing or implementing one of the programmes, providing rich, practice-grounded insights. While we do sometimes generally compare the national biogas programmes of Nepal and India, based on stakeholder accounts, the empirical focus is on TLAD policy implementation and diffusion within the specific localities. Accordingly, the findings are not intended to be nationally generalisable; they should be read as illustrative cases of how national programmes can manifest in local contexts in Nepal and India and how through taking a wider, historical lens to transitions, they can be understood much better.

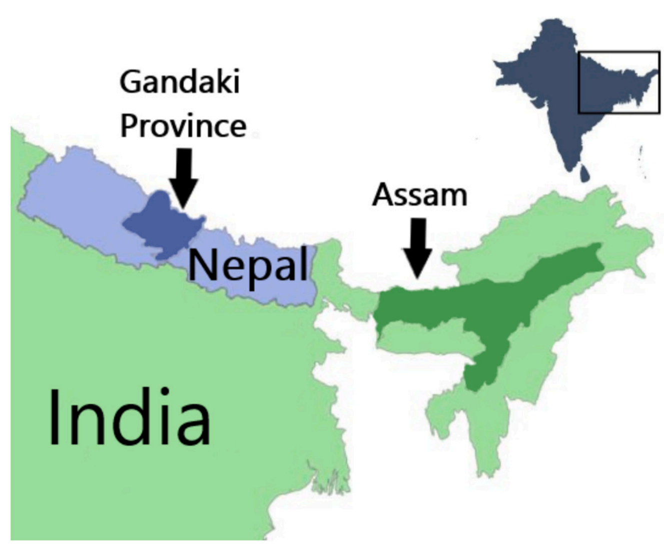

Fig. 1. Map of Nepal and Northeast India, showing the case study regions: Gandaki Province (Nepal) and Assam (India). Inset: location of the study areas within the Indian subcontinent.

Table 4
Timeline of Nepal and India's national biogas programmes including major actors and events [18,25,29,91].

Year and large events	Nepal	India
Before the 1950s 1947 – India gains independence from British rule	**1947 –** First biogas digester constructed	Biogas development pioneered by agricultural researchers
1950–1980 1973 – Oil crisis 1973 – National parks created in Nepal to protect forested areas	**1968 –** KVIC demonstration in KTM **1974–75 –** Agriculture year - government supported dissemination of biogas digesters with the ADB/N **1977 -** GGC created – private company with local offices – subsidies from ADB/N and international organisations	KVIC design promoted by KVIC as a rural development initiative for small and medium farmers **1975 -** The first large-scale biogas diffusion programme was the All India Co-ordinated Biogas Programme
1980–1990 1989 – India fuel blockade in Nepal	GGC led programme	**1981–1985 -** NPBD was set up under the responsibility of the Ministry of Agriculture with the KVIC and Action for Food Production (AFPRO) **1981 –** Department of Non-Conventional Energy Sources created (later called the Ministry of non-Conventional Energy Sources and now called the Ministry of New and Renewable Energy (MNRE) **1982 –** Department of non-Conventional Energy Sources take over programme renamed NPBD
1990–2000s 1990s – Economic liberalisation in Nepal and India, opened up economies to foreign investment and markets 2015 – Nepal earthquake 2016 – India fuel blockade in Nepal	**1991 –** The government, ADB/N and GGC proposes the involvement of the SNV **1992 –** Formalisation and initiation of SNV/ BSP in Nepal. BSP a dedicated organisation for the promotion and dissemination of biogas technology **1996 –** AEPC created **2010 –** AEPC take over the programme **2017 –** International financial aid stops	**2005 –** the NPBD was renamed the NBOMP **2017 –** Programme renamed the new NBOMP (NNBOMP)

4. Biogas programme history and structure

Prior to reading the Findings, it is essential to understand the socio-technical context and historical evolution of Nepal and India's biogas programmes. This section offers a historical overview of each programme, detailing the key institutions, significant historical events, and governance structures, also summarised in Table 4.

4.1. Nepal

In response to the oil crisis, the Government of Nepal (GoN) supported the first biogas programme in 1974 [32,89]. The Ministry of Agriculture supported the construction of domestic biogas plants with interest-free loans from the Agricultural Development Bank Nepal (ADB/N). In 1977 a private limited company, the Gobar Gas Company (GGC) was established, kick-starting Nepal's long term public private approach to biogas implementation. From 1992 to 2010, international donors including the Netherland's Development Organisation (SNV) provided financial aid and technical assistance, accelerating biogas installations [12,34]. During this period, the Biogas Support Program (BSP) was launched to promote biogas, train skilled staff, and build the capacity of Nepal's biogas programme. The BSP facilitated financial installation costs by providing subsidies that were only reimbursed to the private companies if they built satisfactory models [90]. The ADB/N continued to provide affordable financing to farmers by offering loans to cover the capital cost of biogas. While biogas development in Nepal was being kickstarted the GoN also began nationalising forests and restricting the access that rural people had to their forest based livelihoods which incidentally creates needs and motivations for biogas [32]. Overtime the promotional discourse around biogas shifted towards forest protection.

In 1996, a government ministry called the Alternative Energy Promotion Centre (AEPC) was created to take over promotional activities, policy development and funding coordination when the SNV supported phase came to an end. The AEPC fully took over the programme in 2010 [12]. In 2005 the AEPC registered the domestic biogas programme as a Clean Development Mechanism (CDM), aiming to cover future subsidies and maintenance costs through carbon payments instead of donor financial support.

4.2. India

The first biogas model widely disseminated across India was developed by the Khadi and Village Industries Commission (KVIC).[2] The KVIC was predominantly responsible for promoting biogas for rural development during the 1960s and 1970s along with the Central Ministry of Agriculture, who provided subsidies. In 1981, the National Programme for Biogas Development (NPBD) (1981–1985) [91] was created under the Ministry of Agriculture. The ongoing oil crisis of 1973 led to the creation of the Ministry of Non-Conventional Energy Sources [25], later called the Ministry of New and Renewable Energy (MNRE) which took over the NPBD. The programme design was very top-down and heavily reliant on subsidies and construction targets. In 2005, the programme was renamed the National Biogas and Manure Management Programme to make biogas a holistic rural livelihood solution [29].

The programme, now called the New National Biogas and Organic Manure Programme (NNBOMP), adopted a decentralised multi-agency and multi-model implementation strategy. Subsidies and financial assistance are provided by the MRNE, centrally through a top-down model [30] and assigned to each state [15]. The State Nodal Agency (SNA) for each state oversees construction, training and maintenance and subsidy allocation along with the KVIC and Biogas Development and Training Centres. The SNAs are organised differently in each state [16] and successful implementation depends on the state capabilities as well as involvement of various informal actors. The SNAs are supposed to send reports to MNRE regarding the number of plants installed in the state and how many of them were functional/non-functional but a report in 2015 found that many states often fail to do this and so it is unclear how successful the biogas programme is [92].

[2] KVIC is a statuary body, established in 1957, by an act of parliament. The wider objectives of the KVIC are to build a stronger rural community.

5. Findings

Nepal and India's domestic biogas programmes share a centralised structure with nationwide policies that provide households subsidies for constructing biogas digesters. They also offer additional incentives for connecting household toilets and for co-digesting human excreta with cattle dung and other organic waste. Nepal has notably succeeded in executing its sanitation policies, resulting in a significant number of households connecting household toilets to their biogas digesters. In contrast, India has made more limited progress, with only a few localities widely recognised for successfully implementing similar initiatives. This disparity underscores the varying effectiveness of national sanitation strategies and their actual impact on community-level sanitation practice. Stakeholder interviews revealed that this variation in TLAD uptake arises from a complex interplay of factors, including governance at both central and local levels, policy execution, cross-sector policy coordination, the agency of formal and informal actors, and the socio-political, economic, geographical, and historical contexts mediating policy outcomes. These intricacies, while multifaceted, were categorised into five main themes through the coding process, which are presented in the following section.

5.1. National energy transition narratives

Stakeholders frequently situated household biogas adoption outcomes within the wider energy landscapes of Nepal and India, highlighting how they shape both policy design and household decisions. Several respondents described how evolving national energy narratives frame household transitions to TLADs and domestic biogas, with shifting narratives influencing not only policy priorities but also household fuel choices and technology uptake. The national narratives around energy and specifically LPG which is used as a cooking fuel in Nepal and India differ significantly: Nepal focuses on minimising LPG use and achieving energy independence, whereas India emphasises increasing LPG usage. These narratives shape the policy environment in which biogas programmes operate and influence the culture and narratives within rural kitchens.

Nepal's energy landscape has been historically unstable and supportive of domestic biogas as a means of managing energy security and affordability [12]. Nepal has the capacity to generate sufficient electricity from hydropower but has not realised this potential [93,94], leaving the country reliant on fossil fuel imports from India [95]. Energy security has repeatedly been undermined by international relations and natural hazards. The Indian fuel blockades of 1989 and 2015 were disastrous for Nepal and pushed many households back to using firewood for cooking [95]. Nepal faces energy deficits caused by natural hazards, including earthquakes and landslides, which can disrupt fuel and other supplies transported by road [96]. The mountainous geography and poor road transportation to some areas in Nepal can make LPG up to four times more expensive than it is in urban areas due to transportation costs [96]. Collectively, these dynamics illustrate how a culture of energy resilience has emerged [95,97,98], shaping both household transitions and programme design. In Nepal *'The government has made a target that by 2030, penetration of LPG should not exceed 39% [of households] (expert stakeholder #1)'*.

In India, stakeholders discussed that LPG is a more prevalent household fuel, promoted and subsidised by the government, and often leveraged as an election vote winner. The MNRE itself has attributed shortfalls in biogas adoption to the increasing availability of domestic LPG, as well as the free LPG connections offered to many potential biogas beneficiaries [92]. However, this political narrative might not accurately reflect the reality of rural Indian kitchens where households commonly fuel stack. As one stakeholder highlighted, *'rural households that get LPG [subsidised] from the scheme have no money to get [LPG] refills every month so they may have LPG, but they have gone back to fuel wood (expert stakeholder #6)'*. LPG is often sold at prices higher than the subsidised rate within informal markets in rural areas.

Differences in the national energy landscapes of Nepal and India are evident in LPG penetration: recent health surveys in both countries estimate that 42.3 % of rural households in India rely on LPG or natural gas compared to only 19.6 % in Nepal [74,82]. In Nepal, biogas is promoted alongside government efforts to reduce LPG dependence and strengthen energy independence from India. In India, by contrast, biogas promotion occurs in a setting where LPG expansion is actively encouraged and even leveraged as an electoral tool. These dynamics frame the two national biogas programmes within markedly different contexts.

5.2. Unique socio-cultural specificities

Some households interviewed in Assam described Nepal's culture as potentially being less orthodox compared to India's. *'See … my relatives live in Nepal…many young boys go abroad [to work]…they see the world and become educated about what is going on…The mentality of people of Nepal has changed. So, I don't think there are problems around installing TLADs in Nepal (M 34 Hindu U25 Assam)'*. Stakeholders linked this perception among households in Assam to Nepal's historical trajectory, particularly the civil war and subsequent migration patterns. The civil war in Nepal (1996–2006) challenged entrenched hierarchies, particularly the dominance of high-caste landowning elites who controlled much of the rural economy and political system. This conflict had various socio-economic implications including a reinstatement of it's multi-ethnic origins and advances in women's empowerment [100–102]. Alongside other socio-environmental factors, such as the search for employment, the war contributed to large-scale migration to urban centres and abroad [103]. Such migration, stakeholders as well as householders in Assam suggested, may have relaxed some socio-cultural norms by exposing migrants to new ideas and experiences.

In contrast, India was colonised under British Imperial rule until 1947. The British, among other atrocities, formalised and strengthened the caste system in many ways, not limited to, the granting of land and government jobs to higher castes and the formalisation of the work of sanitation workers to the lowest castes [104,105]. While both countries have predominantly Hindu populations, stakeholders noted that each has undergone distinct historical and societal trajectories. These differences have shaped contemporary socio-cultural norms and the ways in which they are expressed and negotiated. They are also likely to influence how socio-technical transitions involving taboo technologies such as TLADs unfold, both at national scale and across different localities.

Expanding on this, stakeholders #2 and #11 specifically highlighted how cultural distinctions at the local level impact transitions to TLADs. '*There are certain areas (in Nepal) where it seems to be a cultural barrier. Near the Indian border people—especially young men—don't want a biogas system in their house. I don't know why; it's really a dilemma. All the women want biogas, but the boys don't. And in some areas, if the head of the household, the father, uses the toilet, then his son-in-law cannot use that same toilet (expert stakeholder #11)'*. In contrast to this, in Gandaki Province there a significant presence of Janajati or ethnic groups. These groups are known for practicing much more relaxed ritual caste practices and gender norms compared to Hindu castes and thus provide a notable diversity to the range of socio-cultural norms across Nepal's Provinces. While only two interviewed households self-identified as Janajati, the broader demographic presence of these groups in the region may influence the local socio-cultural backdrop more generally. Many people in the Kaski district were also recruited into the Gurkha armies for over 200 years and the area has been shaped by a long history of out-and-return migration and remittances [106] which would have also brought cultural influences. Perhaps Gandaki Province has a socio-cultural backdrop more conducive to TLAD adoption than other localities in Nepal. Household interviews in Gandaki Province indicate that transitions to TLADs were gradual: while initial opposition to TLADs did exist, households renegotiated norms when supported by favourable conditions with sufficient time [73]. Socio-cultural opposition is likely more renegotiable in some localities of Nepal than others, though it remains unclear whether non-adoption elsewhere (such as the context stakeholder #11 highlighted above) is due solely to cultural norms or also to the availability of alternatives and other contextual factors.

Assam has almost three times the average Muslim population of the all-India average and subsequently fewer people that identify as Hindu presenting a different socio-demographic landscape to all India average. Cattle and livestock rearing practices are closely tied to religion and ethnicity: many Nepali Hindus migrated to the Brahmaputra valley in Assam due to its suitability for cattle rearing and because the British encouraged this migration during colonial rule [107]. It is common for lower socio-economic groups, non-Nepali-Hindus, to keep pigs instead of cattle [108,109]. While it is common to use pig dung as a biogas feedstock in China and Vietnam, India's biogas programme requires households to own cattle to be eligible [110]. Expert *stakeholder #2* emphasised that this design excludes the very groups who might have the greatest motivation to adopt biogas—poorer households who do not always own cattle or lots of cattle. By contrast, households with larger cattle holdings tend to have greater financial means and are more likely to access LPG. Consequently, programme criteria risks privileging these better-off groups [10] and overlooking households with the greatest potential motivation to adopt biogas.

This study does not aim to draw reductive conclusions about local cultural differences. However, stakeholder interviews frequently highlighted the diversity within socio-cultural norms as an important theme. The local socio-cultural descriptions are presented not to generalise but to provide contextual grounding for understanding each local transition before presenting the broader findings. The unique socio-cultural environments of the case study locations undoubtedly influence how TLADs diffuse locally and affect the effectiveness of national policies. However, interviewees did not frame these socio-cultural norms as rigid barriers but rather as dynamic factors that interact with programme design, policy approaches, and household decision-making, though sometimes they can be the dominant deciding factor for or against adoption, but importantly, not always. This perspective challenges the common portrayal of socio-cultural norms as the dominant constraint and instead positions them as mediators of transition within broader structural and institutional frameworks.

5.3. Top-down and horizontal governance

Despite criticisms of international aid for its top-down approach and its many failures often attributed to programmes being disconnected from local realities [111,112], Nepal's biogas programme stands out as a successful example of top-down implementation. Stakeholders #5, #9 and #13 explained how a top-down vision and implementation strategy facilitates biogas diffusion. Biogas technology is complex, labour-intensive, and, when connected to a toilet, can carry cultural taboos. Promotional activities, inclusive of opportunities to observe and trial biogas technology, are required over long time periods before many households choose to adopt TLADs. While bottom-up demand for biogas technology may emerge over time, initial top-down promotional efforts are crucial to generate awareness and demand. A top-down governance approach ensures that biogas is actively promoted, subsidies are provided, and critical support activities—such as awareness campaigns, training, maintenance, and regulation—are implemented to facilitate user adoption.

Nepal's biogas programme is an example of how more top-down, centralised structures can coexist with more horizontal, decentralised governance [113]. Initially managed by the BSP, a dedicated implementation agency, the programme benefited from a hybrid governance model. The BSP acted as both the centralised managing body and the implementation agency, enabling it to oversee the programme while actively engaging with stakeholders such as private-sector implementation companies and users within various local contexts [18]. Stakeholders explained that this dual role facilitated a more horizontal governance structure by creating shorter feedback loops between policy developers and implementers, thus fostering more direct and non-hierarchical communication. Drawing on this insight, we considered India's programme structure for comparison. Unlike Nepal, India's biogas programme is centrally designed by the MNRE but implemented by SNAs within various government departments. This design adds a hierarchical layer between policy design and implementation, which may restrict feedback flows and reduce adaptability at the local level. Although stakeholders did not explicitly frame this point in these terms, it emerged from the comparative coding of their accounts. Reflections on Nepal's programme repeatedly prompted comparison with India's, drawing attention to structural differences that may constrain responsiveness. In India, centrally designed policies are interpreted and operationalised by separate SNAs, so programme implementation varies by state and is shaped by how each agency integrates biogas with other state-level programmes and policies.

In the case of TLAD diffusion, horizontal governance proved particularly effective in Nepal's biogas programme. BSP stakeholders actively engaged with communities, educating them on the benefits of TLADs, learning how to support their adoption in practice, and actively facilitating transitions. Recognising that immediate toilet connections were unlikely for many households, they adopted a phased approach to encourage gradual adoption. This strategy included implementing an informal, yet widely enforced, policy requiring households to install an additional pipe to their biogas digesters for future toilet connections. This proactive measure ensured that households faced no technical barriers if they later decided to connect their toilets: a decision many ultimately made. To further promote adoption, implementing actors from the BSP and private biogas companies identified "progressive" households willing to connect their toilets immediately. They then organised visits for other households to see these systems in operation. As one stakeholder explained, they would take "*all these [other] users to [their] farm and show them… this is biogas that goes to kitchen. It is no different to yours [biogas without a toilet connection] (expert stakeholder #9)*'. This combination of demonstration and forward-thinking policy was instrumental in the nationwide diffusion of TLADs in Nepal. We presume that this tactic has not promoted TLAD adoption everywhere around Nepal, as reflected in the earlier quote from stakeholder #11, but stakeholders said it was a very effective way of convincing many households to renegotiate socio-cultural norms around TLAD use all over Nepal.

5.4. Commitment of programme stakeholders to enact policies

Stakeholders highlighted that the successful implementation of Nepal's policies, particularly the promotion and adoption of TLADs, was largely attributed to the commitment of programme actors who translated policies into practice. Expert stakeholders interviewed were unable to pinpoint specific reasons why this occurred in Nepal but not in India. However, analysis suggests that the difference arises from a combination of cultural, political, and programmatic factors unique to each context, though these are difficult to define or quantify precisely. This section outlines a few of the key factors identified during the discussions.

One key difference between the two programmes may lie in the organisational structure of the implementation agencies. In Nepal, the BSP functioned as a specialised biogas promotion and implementation agency. In contrast, India's biogas programme is managed and implemented by national and state government departments, where biogas is just one of many responsibilities. Stakeholders indicated that these government departments often lack the specific expertise, dedicated workforce, and sufficient funding required to effectively execute a successful biogas programme, significantly affecting the promotion and adoption of TLADs. '*In the policy paper it mentions there should be regular monitoring of the systems…Government of India cannot monitor all …[28 states and 8 union territories] it is not possible… But [the state] nodal agency,* *practically, they do not have sufficient manpower, sufficient infrastructure (expert stakeholder #8)'*. Furthermore, biogas implementation depends on individual actors' agency, making it vulnerable to changes in government priorities because *'if the government changes, then [jobs] change hands and [biogas and rural development] doesn't become a priority for some of the members (expert stakeholder #2)'*. The execution of India's biogas programme is shaped by the overarching goals of the managing departments. Managed by the MNRE, the programme is likely to prioritise an energy-centric approach. This is further reflected in Assam, where the SNA operates under the Department of Environment and Forests, which focuses on reducing deforestation. As a result, biogas in Assam is primarily viewed as a replacement for firewood, reinforcing an energy-focused strategy [29]. One stakeholder said there will likely be *'a more engaged approach from the forest department in some villages [close to forests]. And those are the villages where if biogas has not worked, they have got an engineer to come in and fix it (expert stakeholder #2)*'. A toilet connection to improve sanitation does not align with the Department of Environment and Forests' mandates or areas of expertise.

Nepal's biogas programme, now managed by the AEPC, has faced significant challenges since transitioning to a government-led model. Many stakeholders believe that *'the management of the programme… [has] totally failed (expert stakeholder #5)'* due to a shift towards a more top-down approach focused on construction targets [12,114] with reduced regulation. One noted, *'The quality and control part [is now] very relaxed… so there were many incidents where I heard of complaints (expert stakeholder #13)'*. These inefficiencies resemble those in India's NNBOMP, highlighting the benefit of having dedicated, specialised implementation agencies for biogas programme success. However, this requires further investigation as the AEPC's takeover coincided with the withdrawal of international funding, leading to resource constraints [12]. While the AEPC recognises the importance of supportive activities beyond technical subsidies, stakeholders reported difficulty in securing government funding for these efforts, *'because [the] government has very limited resources and in many instances, they see the technical assistance activities as non-essential (expert stakeholder #1)'*. Additionally, global factors have impacted the programme: Stakeholder #1 drew attention to rising cement prices which have increased construction costs, and the fact that many masons trained under the biogas programme have left to work in other sectors, creating a skilled labour shortage and necessitating continual investment in training. These socio-technical pressures have further hindered the programme's effectiveness in Nepal.

Some stakeholders highlighted the few successful TLAD diffusion case studies in India, attributing these successes primarily to informal actors or local institutional support, rather than official biogas programme policies or NNBOMP actors. One notable example is in Gujarat, where TLAD diffusion was driven by a local dairy cooperative in collaboration with national and international partners [27,28]. Stakeholder #8 said that local actors independent of the government programme invested considerable effort in sensitising users over time, focusing on improving local sanitation and biogas outputs [27]. This suggests that TLAD success in local Indian contexts may depend less on the formal programme framework and more on local informal actors, as well as on whether the SNA chooses to promote TLADs as part of its mandate.

Stakeholders #4 and #2 suggested that India's lack of political commitment to promoting TLADs reflects the GoI's broader reluctance to address social challenges directly. They argued that, politically, there is a significant distinction between having policies that promote TLADs and government departments actively advocating for them. Actively pushing TLADs would require publicly endorsing a taboo technology that challenges cultural beliefs about purity and pollution, potentially alienating some voter groups. The example of the GoI's Swachh Bharat Mission (SBM) or 'Clean India' mission was discussed with stakeholders to put this paradox in context. Stakeholder #4 drew attention to the fact that despite the SBM's success in enhancing sanitation coverage, it has largely ignored the rights and welfare of manual scavengers,[3] who continue to be employed across India [105]. Thus, while toilet provision has increased, the SBM's technocentric approach has done little to tackle social inequalities surrounding sanitation work. In Assam, biogas programme actors showed more resistance to TLADs than many households that were interviewed [29,46]. An SNA officer articulated that they believed people in Assam would not agree to link their toilets to biogas because of religious and cultural reasons [29]. Exploring the socio-political complexities surrounding the GoIs commitment to TLADs is beyond the scope of this study but this brief discussion is included to illustrate that the socio-cultural resistance to TLADs, typically attributed to users, is likely intertwined with broader political and societal frameworks. Asserting that TLAD adoption failures are solely due to user resistance, while overlooking political sentiment, oversimplifies reality and misrepresents the underlying complexities.

5.5. Multi-sector coordination

Many stakeholders stressed that the reason Nepal's programme successfully promoted TLADs was because the BSP coordinated with sanitation initiatives. The '*principle driving factor [for promoting toilet connections] was the [sanitation promotions]…together with the subsidy that was granted by the government [for toilet connections]. Because it made sense, I think the biogas and the toilet together* (*expert stakeholder #5*)'. Nepal's biogas programme was effectively integrated with sanitation efforts, promoting TLADs through rural sanitation campaigns. Sanitation personnel promoted TLADs as a sanitation solution, and masons building toilets were also trained to construct TLADs. This coordinated approach helped imbed TLADs within broader sanitation efforts. In Gandaki Province, household interviews highlighted the programme's effective coordination. Several households indicated that the primary motivation for adopting TLADs was the improved sanitation benefits. They noted that during the TLAD promotion period, local authorities were also issuing fines for open defecation, which further incentivised the adoption of TLADs.

It is written within India's biogas programmes policy that the NNBOMP should coordinate at the state level with the SBM for a multi-sector approach. However, the programmes do not, to our knowledge, formally coordinate at the national or the state level of Assam. Whether they have in other states could not be found in documentation. One stakeholder said that the NNBOMP and the SBM had tried to combine their efforts and subsidies for toilet connected biogas at the national level but the department of finance *'objected. [They said] it is not feasible because there are two different ministry funds (expert stakeholder #8)'*. Ultimately this means that the SBM and NNBOMP central policies are designed and implemented separately, with households being offered competing solutions from two different programmes. TLADs are included within the official the SBM information [115] but they are not subsidised through the SBM as far as we could determine. The predominant sanitation solution that is promoted, installed and subsidised across India, is the basic pit latrine [105]. Many households interviewed in Assam said that they had no need for a TLAD because they have an existing sanitation solution.

[3] Manual scavengers are sanitation workers who manually clean human waste for a living and face considerable occupational health risks. They are subject to caste-based stigmas around ritual pollution which result in a dangerous substandard working conditions and lack of social mobility with women facing the greatest hardships [19,105]

6. Discussion

Socio-cultural resistance is often cited as the primary barrier to TLAD adoption, but this study provides evidence that it is not a standalone cause of failure. The findings highlight that systemic factors such as governance, policy coherence, and the agency and commitment of programme actors can play an equal or greater role by interacting with socio-cultural norms in shaping household transitions. In addition, the wider socio-technical backdrop, including localised historical cultural trajectories and national and local energy narratives, conditions the environment in which households make decisions. All together, these factors influence whether socio-cultural norms manifest as opposition to TLADs or are instead renegotiated within local contexts in ways that enable their adoption.

Despite their critical importance, these higher-level factors have received insufficient research attention. In India, a narrow focus on socio-cultural resistance has unjustly attributed failures to households, while overlooking broader systemic challenges such as competing technologies promoted without policy coherence and a biogas programme structured in ways that leave toilet connections dependent on whether state departments responsible for TLADs choose to prioritise them. By contrast, in Nepal the contributions of programme actors, the development of more coherent policies and approaches that integrate biogas with sanitation initiatives, and the country's distinctive geography, which supports its ambition for greater energy independence, have been largely underappreciated in biogas research as key determinants of TLAD success, despite being central to the transitions observed.

The findings draw attention to a critical gap in biogas research as well as, we believe more broadly, in the clean cooking sector, where biogas is just one of many potential solutions. While cooking practices, inclusive of the fuels households select, are among the most extensively studied energy service areas, much of the research disproportionately focuses on the household level [96]. This narrow perspective has led to an overemphasis on user or community decision-making as the primary determinant of success or failure, neglecting higher-level factors such as policies, policy coherence, programmatic design, and the role of the socio-technical backdrop in shaping opportunities for biogas to replace existing alternatives. The narrow focus on the household level fails to capture the full complexity of household transitions to a new technology. We add to voices, such as by scholars Bharadwaj et al. [96], Abdelnour, Pemberton-Pigott, and Deichmann [116], Batchelor et al. [117], and Khandelwal et al. [118], that advocate for research to broaden its focus to include higher-level contextual factors when examining household transitions to new cooking practices.

The interpretation of socio-cultural resistance as a barrier to technological progress has roots in colonialism and early international aid, which often viewed socio-cultural norms as impediments to technological and economic development [112,119–121]. Through a Western lens, religion and culture are reserved for the personal realm, not the practical and thus, do not belong in the physical realm [122–125], Yet, in many cultures, religion and culture are a part of the physical [22,126]. Socio-cultural norms should thus be viewed as an inherent part of the socio-technical backdrop of a transition, shaping the adoption of biogas, not a barrier to be overcome [127,128]. A more integrated approach to domestic biogas investigations that does not frame socio-cultural norms as alien or antagonistic to technological innovation is required. Even implementation programmes and research that adopt a socio-technical lens can reinforce the perception of local socio-cultural practices as barriers if these practices are labelled as such [56,128]. We argue that the research community must reevaluate the language and discourse within sustainability transitions research in Global South contexts to foster a more holistic and inclusive understanding of the interplay between socio-technical systems and socio-cultural dynamics. Just as the "Not In My Back Yard" (NIMBY) framing of local resistance to sustainable technologies like wind farms has been critically challenged in Global North contexts, we contend that the concept of socio-cultural resistance—more often used as NIMBYism's counterpart in Global South contexts—should be similarly scrutinised and reframed to avoid oversimplification and ensure deeper engagement with systemic factors [46,129,130].

Methodologically, this study demonstrates the value of applying a sustainability transitions framework to improving understanding of the root causes of why TLADs succeed in some contexts but not others. We believe this study provides valuable methodological development, demonstrating how a transitions approach can be effectively utilised to enhance understanding of domestic biogas diffusion, building on prior research in this area [65–69]. By employing this approach, the analysis advanced beyond previous research, taking an interdisciplinary perspective to examine cross-sectoral and multi-level influences on TLAD transitions. The approach also explored how these factors interact to shape transitions as part of a holistic system, incorporating the socio-technical backdrop and the unique opportunities and challenges it presents for TLAD diffusion in specific case study contexts. The use of a qualitative approach, employing semi-structured interviews with expert stakeholders, was fundamental to this study's ability to uncover previously inaccessible information. This approach revealed insights known only to a small circle of individuals directly involved in or deeply knowledgeable about the programmes. It also facilitated making connections between different aspects of each programme, such as the relationship between policy coherence at the national and local levels and its impact on household transitions. Much of the information shared in these interviews had not been formally documented, making the perspectives and accounts of the expert stakeholders critical for understanding the nuanced interplay of factors influencing transitions.

This study offers a novel and broader conceptualisation of domestic biogas transitions than has been offered to date. By analysing two case studies in two countries with some of the longest-running biogas programmes, it brings together local and national dynamics to theorise why TLADs succeed or fail under the same or comparable programmes and contexts. While the case studies cannot represent entire national contexts, the approach advances understanding, demonstrating how a sustainability-transitions lens can capture overlooked dynamics of programme design, governance, and socio-technical historical developments. In this way, the study contributes a foundation for future work and offers insights for researchers, and potentially policymakers and implementers.

Additionally, the approach adopted in this study offers significant learning potential for investigating sustainability transitions in the Global South more broadly, where decentralised solutions like TLADs are common. This methodological experimentation, and the demonstration of its effectiveness in studying transitions to a decentralised technology in Global South contexts, is timely and aligns with growing calls for expanded application of sustainability transitions research in these regions [58,60]. We hope this study provides valuable insights and contributes to learning within the research community.

7. Conclusions and recommendations for research and practice

This study set out to examine why Nepal's domestic biogas programme has been more successful than India's in supporting household transitions to TLADs within local socio-technical regimes. This comparison is important because both countries have broadly similar programme policies and, at a high level, comparable rural socio-economic characteristics, within which socio-cultural norms can act to discourage adoption and use. Both countries also run long-standing nationwide biogas programmes offering financial subsidies for TLADs. The research was motivated by the lack of studies that challenge the prevailing narrative that local socio-cultural resistance is the primary barrier to TLAD adoption. It also built upon two earlier household interview studies in Nepal and India, which provided strong evidence that household transitions are influenced by a range of factors extending well beyond socio-cultural norms [46,73]. This study addresses that gap by examining socio-cultural norms alongside higher-level programmatic and contextual factors such as governance, policy coherence, and socio-technical conditions that shape transitions and household decision-making.

The study employed a sustainability transitions framework in combination with a comparative case study design, examining successful TLAD adoption in Gandaki Province, Nepal, and contrasting it with unsuccessful transitions in Assam, India. While socio-cultural norms do shape and influence household decision-making, the findings highlight that systemic factors—such as governance, policy coherence, and the agency and commitment of programme actors—can play an equal or greater role in determining the success or failure of transitions to TLADs. These factors also interact with socio-cultural norms, influencing whether they manifest as opposition to TLADs or can be renegotiated in local contexts to facilitate adoption. Equally important is the broader socio-technical backdrop, in which the historical evolution of energy policies, socio-cultural practices, and migration patterns generates localised contexts that condition household decision-making and mediate the influence of programme policies on transition outcomes. Although higher-level factors are critical, they remain insufficiently addressed in existing research, which often concentrates on households while disproportionately attributing failed transitions to socio-cultural resistance. By taking a conceptual step towards bridging these gaps, this study proposes a more nuanced understanding of the drivers and barriers to TLAD adoption. It also offers evidence to move beyond socio-cultural resistance as a default explanation, redirecting attention to programme- and system-level dynamics when evaluating failed transitions.

This study also underscores the importance of recognising when TLADs may not represent a viable or necessary solution within a given context. Rather than attributing resistance solely to users, the findings highlight the need to assess whether prevailing socio-technical conditions are conducive to adoption or not. Where such conditions do not generate sufficient incentives, for example in Assam where households already had access to adequate alternatives, expecting households to renegotiate socio-cultural norms may be unrealistic. In such cases, attributing non-adoption exclusively to socio-cultural resistance is overly reductive and obscures the underlying contextual realities. This perspective shifts the focus from overusing socio-cultural resistance to critically assessing programme design and contextual appropriateness. We contend that framing user behaviour as the central barrier to TLAD dissemination has unfairly shifted blame onto potential users by portraying them as resistant to change, thereby perpetuating an out of date and technocentric framing to development [127,128]. This perspective has also limited critical discussions about the feasibility of TLADs as effective solutions for rural challenges. We propose that because of this, research and practice might have neglected opportunities for a more comprehensive assessment of biogas programme design, support structures, and the socio-technical conditions required for successful outcomes. We advocate that future research avoids citing socio-cultural resistance as the sole reason for failed transitions without situating it within an analysis of programmatic and policy contexts, which shape how such norms manifest in technological transitions.

The findings are not only significant for research but also offer valuable practical insights for promoting and implementing TLADs, with potential applicability across various geographical contexts. They emphasise the advantages of operating biogas programmes through dedicated implementation agencies rather than government departments where biogas is just one of many of their competing responsibilities. Specialised implementation agencies can offer knowledgeable, focused, and sustained support, which is essential for the successful diffusion of biogas technologies that require long-term commitment and expertise to drive adoption. The study also underscores the need to move beyond an overreliance on upfront subsidies as the primary strategy for TLAD diffusion. While financial incentives are important, long-term support mechanisms and consistent community engagement are crucial for sustained adoption. Only offering subsidies for the upfront cost of the digesters is ineffective if programmes do not have the means to facilitate their sustained integration into local socio-technical systems through training, maintenance and market support. These insights highlight the importance of designing biogas programmes that prioritise both implementation quality and long-term impact.

Effective governance is another critical factor for improvements in practice. Stakeholder accounts explain how one promising approach is a top-down, decentralised governance model that can adapt to local contexts while incorporating grass-roots input and feedback, thereby enhancing the effectiveness of programmes promoting TLADs. In practice, this means that central policies can set the overall framework and provide momentum, but implementation must remain flexible enough to respond to local socio-cultural and economic conditions. Ensuring policy coherence and adapting policies to local contexts are also crucial. Supportive biogas policies can be undermined by unsupportive ones from other sectors such as subsidised LPG and chemical fertiliser. Policies must be designed to align with local needs and conditions, which requires ongoing assessment and adaptation.

Expanding this research with additional case studies in Nepal and India would provide deeper insights into how and why TLADs diffuse across diverse localities. Including further case studies in India where TLADs have succeeded, such as Kerala or Gujarat [27,131], alongside a location in Nepal where TLADs have failed to penetrate local socio-technical regimes—could shed light on both intra- and inter-country variability. Such comparisons would deepen our understanding of how national policies translate into local contexts, and why outcomes diverge based on programme governance and local socio-technical conditions. This information would be invaluable for understanding the successes and failures of each biogas programme.

Expanding the geographic scope beyond Nepal and India could also offer a broader perspective on the global relevance of the findings. Moreover, integrating geographic mapping could enrich the qualitative approach used in this study. Prior research in Nepal has shown that factors like road access significantly shape biogas adoption patterns [11,96]. Mapping TLAD diffusion alongside LPG usage, sanitation and fertiliser access, or proximity to implementing agencies could yield deeper insights into spatial and systemic influences—particularly in relation to policy coherence and delivery quality.

CRediT authorship contribution statement

Natalie Boyd Williams: Writing – review & editing, Writing – original draft, Methodology, Formal analysis, Data curation, Conceptualization. **Ben Campbell:** Writing – review & editing, Supervision, Methodology, Conceptualization. **Debadayita Raha:** Writing – review & editing, Supervision. **Debendra Chandra Baruah:** Supervision, Data curation. **Marc Kalina:** Writing – review & editing, Visualization. **Elizabeth Tilley:** Writing – review & editing, Supervision. **Jennifer Dickie:** Writing – review & editing, Supervision, Methodology, Conceptualization.

Declaration of competing interest

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

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.erss.2025.104496.

Data availability

Data will be made available on request.

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