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The influence of exogenous elements on technological innovation system development: The case of rainwater harvesting for irrigation in Kenya

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ABSTRACT: Rainwater harvesting for irrigation can increase sustainable access to irrigation and improve farmer resilience to climate change, particularly in semi-arid regions of sub-Saharan Africa. However, attempts to increase adoption of rainwater harvesting for irrigation in Kenya have rarely been successful, despite decades of efforts by governments, NGOs, and development practitioners. Most scholars investigating reasons for these low levels of adoption tend to focus on hydro-geological, techno-managerial, or socio-economic factors, and leave out explanations grounded in the analysis of macro-level cultural, political, economic, and environmental dynamics within a specific context. To fill this gap, this article analyzes historical processes of two sites to identify how these dynamics contributed to an enabling environment for rainwater harvesting for irrigation in Kenya. The concept of technological innovation systems, which describes processes central to the emergence, growth, and diffusion of technological innovations, was used as a lens to examine long-term rainwater harvesting for irrigation adoption dynamics in the two sites. The identification of elements «exogenous» to the innovation system demonstrated that ecological, demographic, macroeconomic, political, cultural, and socio-economic elements exerted a major influence on the development of an enabling environment for rainwater harvesting for irrigation. Exogenous elements influenced levels of adoption by shaping the capacity and quality of elements within rainwater harvesting innovation systems, giving rise to systemic problems or opportunities, and influencing the speed of system development.

KEYWORDS: Contextual factors, water harvesting, irrigation technologies, innovation adoption, smallholder, agriculture, Kenya.

1 INTRODUCTION

Over the last fifty years, NGOs, donors, and government agencies have carried out attempts to promote RWHI systems across Kenya, particularly in the more arid parts of the country [1,2,3,4,5,6]. RWHI at the farm level can increase water availability by reducing rainwater runoff, groundwater seepage, and water loss due to evaporation. It can enable farmers to grow more profitable crops that require more water, or provide extra water to increase yields off-season. Access to adequate amounts of water is also a prerequisite for other practices that boost productivity, such as soil management or the use of improved seed varieties. Other positive outcomes of RWHI systems include greater resilience to climate change in areas where levels of precipitation have decreased, or rainfall patterns have become more irregular [7].

A RWHI system can be understood as a technological artifact, or a group of technologies used together for a new purpose and paired with associated practices to achieve desired outcomes. There are in-situ RWHI systems where soil capacity to absorb rainfall is enhanced, and ex-situ RWHI systems, where run-off is collected from a catchment source and stored for later use. This article focuses on ex-situ RWHI systems. Ex-situ RWHI has long been perceived as having enormous potential to improve the livelihoods of smallholder farmers in sub-Saharan Africa by increasing access to water. When possible, farmers adopt irrigation technologies, such as dam liners, pumps, drip lines and sprinkler systems, to increase water productivity and maximize the potential of their ex-situ RWHI system [3,6].

Even though the potential of RWHI in Kenya has been widely acknowledged, efforts to increase uptake have been desultory and sustained adoption rarely takes place. RWHI system construction has largely been carried out by external parties, mainly because its effectiveness depends on technical know-how and relatively high initial investment costs that are often unaffordable to the smallholder farmer. These projects are often unable to catalyze long-term changes in levels in adoption and are hampered by a general lack of accountability or follow-up, a non-participatory approach, lack of farmer capacity to maintain structures, low feelings of ownership due to subsidy dependence, and the insistence on community or group managed systems (as opposed to RWHI for individual farmers) [8,9].

Some scholars have focused on techno-managerial and hydro-geological factors to explain reasons for the low levels of RWHI adoption [10,11,12,13], while others have focused on socio-economic characteristics of individual farmers or households (land tenure, farm size, education level, gender, etc.) that correlate with higher levels of adoption [14,15,16]. These studies tend to be more quantitative in nature. While more qualitative studies do exist, analysis is usually limited to the challenges witnessed in project-based initiatives, such as the lack of technical expertise, participatory planning, and effective operations and maintenance. Recommendations often include improving capacity building, extending credit opportunities, or adopting a more inclusive planning approach, or changing the risk-averse attitude of farmers [17].

In general, there has been little research on longer-term historical processes that have given rise to the cultural, political, environmental, and economic conditions that influence levels of RWHI adoption in a certain context. Like any other technology, uptake of RWHI relies on the existence of an enabling environment that supports its diffusion [18]. To enhance understanding of these conditions and how they contribute to an enabling environment for RWHI, this article uses the lens of the technological innovation systems (TIS). The TIS concept sees innovation as a collective activity and the result of a multi-directional flow of knowledge, where a network of actors and institutions interact to create an enabling environment for a particular technology or artifact to emerge in a specified context [19]. The development of a TIS is essential to the sustained adoption of an innovation, as the presence of an innovation system decreases the time, costs, and risks of adoption [20,21].

Like so many other sustainable technologies (e.g., solar panels or windmills), RWHI TIS development clearly depends on the presence of an enabling environment consisting of certain cultural, political, economic, and environmental conditions. Without an adequate level of rainfall, for example, RWHI is a futile exercise. With abundant rainfall, RWHI is usually an unnecessary one. If there are enough surface water bodies for farmers' irrigation needs, there will probably be little uptake of RWHI, and if soil characteristics are not conducive to growing crops, irrigation will probably not be carried out at all. Besides hydrological and geographical factors, the macro-economic and political environment can also affect RWHI development, adoption, and diffusion. Limited access to input and output markets can circumscribe uptake, as can political priorities that focus solely on the development of large-scale irrigation schemes at the expense of smallholder ones. Demographic and socioeconomic dynamics can also influence levels of uptake, as they shape strategies and investment decisions around household agricultural production [7, 32, 33].

To understand the types of enabling environments conducive to the development of a RWHI TIS, this article focuses specifically on the role of "exogenous elements" that shape TIS development [24, 25, 26,27]. Exogenous elements can be defined as a "set of residual factors that have an impact on innovation and production processes without being influenced by the outcome of innovation processes on a short to midterm basis" [28: 606]. Some examples include world oil prices, economic growth, wars, cultural or normative values, environmental problems, slow-changing societal values, demographic trends, and macroeconomic patterns [29]. Scholars observe that a comprehensive understanding of the factors driving TIS has to be supplemented with analysis of exogenous elements and their influence on the TIS [22, 26, 30, 31]. Exogenous elements shape how actors, institutions, and infrastructures interact with one another around the technological artifact in question, leading to higher or lower levels of adoption [22,23].

To deepen understanding of the type of enabling environment needed for RWHI adoption, a qualitative analysis was used to investigate how exogenous elements contributed to RWHI TIS development in two sites in Kenya where RWHI has been promoted since the 1980s. Specifically, this paper asked: which exogenous elements contributed to the development of an enabling environment for RWHI adoption, and how have they influenced the formation, growth, and maturity of the RWHI TIS in Kenya?

2 THEORETICAL FRAMING

Over the last few decades, the Technological Innovation System (TIS) concept has contributed valuable perspectives on the adoption dynamics of new technologies and technological artifacts. Drawing from the field of evolutionary economics and innovation systems, TIS stresses the importance of diversity, learning, and dynamic interaction in the technological development process [34]. A TIS has several "functions" that influence the development, adoption and scaling of a technology or technological artifact. These functions include entrepreneurial activities, where entrepreneurs capitalize on business opportunities that emerge due to the development of new knowledge, networks, and markets (F1); Knowledge development and learning, where actors learn about the potential uses of the innovation and how it can be improved (F2); Knowledge diffusion, where information about the innovation spreads through interactions between various actors (F3); Guidance of the search, where a clearer vision of the innovation and its potential helps decrease uncertainty for actors (F4); Market formation, where a viable market forms around the innovation to meet increasing demand for the innovation (F5); Resource mobilization, where financial, human and physical resources are mobilized to further develop innovation system formation (F6); and Creation of legitimacy, where the innovation becomes more widely accepted in society and alters the existing socio-technological regime (F7) [35, 36].

TIS development can be divided into different phases– formation, growth, maturity, and decline. The formative phase is generally characterized by large uncertainties, unarticulated demand, absence of positive feedbacks, and technological underdevelopment. Actors focus on research, development, and experimentation to enhance the innovation's suitability. If they succeed and the TIS enters a growth phase, markets begin to take shape and technology-specific institutions emerge. Adoption of the innovation is higher than in the formative phase, but still below potential. Path dependence drives further TIS development, moving it into the maturity phase. In this phase, the TIS benefits from many actors, a high degree of specialization, and low entry/exit rates. TIS performance increases further and begins to branch to new contexts. Eventually, the TIS enters the decline stage, where networks are destabilized, actors begin leaving the TIS, and development slows [37, 27].

The level of TIS functioning in the different phases of its lifecycle can also be analyzed through the presence, capacity, and quality of five structural elements: 1) actors (e.g., producers, companies, knowledge institutions, NGOs, and government bodies); 2) institutions ("hard" institutions that consist of laws, regulations, and rules, and "soft" institutions that consist of customs, routines, and established practices); 3) interactions (networks as well as individual interactions between actors); 4) infrastructure (physical, knowledge-based and financial); and 5) technological artifacts (a group of technologies and associated practices that form the core of the innovation system) [19, 21, 36, 38]. While the first four structural elements are well-established in the TIS literature, the fifth is a more recent addition to analyze the specific characteristics of the technological artifact around which the TIS is formed and differentiate it from other "physical infrastructure", which may include technologies or technological artifacts other than the one that is at the core of the TIS [38]. The development of an innovation system is influenced by the attributes of the technological artifact, which shape actors' decisions to provide supporting functions [39, 28, 40].

The five structural elements of actors, institutions, interactions, infrastructure, and the technological artifact can be deemed "endogenous" to TIS since they operate within the realm of systemic interdependencies around the innovation and directly drive the innovation system's development [22]. The capacity and quality of these endogenous elements are influenced by contextual "exogenous" elements that lie outside the boundary of the focal TIS and influence its development without themselves being immediately affected [22, 41, 42]. Since the boundary separating endogenous and exogenous elements is often blurred, delineation is a subjective analytic choice that depends on the goal of the study. In general, exogenous elements must be sufficiently independent of each other and from endogenous elements to be treated as isolated forces within a specified time period [28, 22, 43]. In this article, exogenous elements are limited to factors at the regional level. Those include ecological, demographic, macroeconomic, political, cultural, and socio-economic factors. Although national and international factors also influence TIS, pressures are translated through actors at the regional level, where innovation processes are deeply impacted by the presence of a common language, local characteristics, and historical patterns [38].

3 METHODOLOGY

To deepen understanding of the role of exogenous elements in TIS development, interactions between exogenous elements and the TIS of RWHI in the Laikipia and Yatta Plateaus in Kenya were studied. Laikipia is in the foothills of Mount Kenya and is primarily located within Laikipia County, while Yatta straddles Kitui and Machakos counties. This study focused on ex-situ RWHI systems in the form of household-level farm ponds that collect run-off from nearby roads or paths after rainfall. Farm ponds have the most potential to provide enough water for smallholder irrigation compared to other RWHI systems [12]. Laikipia and Yatta were chosen as study sites because exogenous elements and levels of RWHI uptake there are relatively well-documented by NGOs and researchers. Moreover, since RWHI has been adopted in these two sites for more than forty years, an "innovation history" approach [44] that allowed for a more in-depth and longitudinal analysis of the effect of exogenous elements on TIS functions could be carried out.

This study used a qualitative approach to collect and analyze data, as the descriptive information necessary to identify relevant processes and causal links between exogenous elements and TIS functions is lacking in existing literature. Rather than follow a linear, stepwise process, this research used retroduction[1] to move between gathering primary data and filling in information gaps with secondary data. Once Laikipia and Yatta were decided upon, data on exogenous elements and the RWHI TIS development were gathered from three major sources. First, nine policy documents and 11 project reports by NGOs and research organizations were used to gather development plans, progress, and agricultural-specific reports from the counties where the study sites are situated and identify relevant information on the RWHI adoption and diffusion in Kenya that reflected donor-led approaches and goals for RWHI.

Second, 97 journal articles and five academic theses were used to gather information specific to exogenous elements and RWHI adoption and diffusion in the study sites, as well as more general information on dynamics present in smallholder agricultural production in Kenya. These articles and theses were sourced from Google Scholar and Scopus using a set of keywords such as “rainwater harvesting” + <study site>”, “smallholder farming” + <study site>”, “history” + <study site>”, but grew more targeted as specific dynamics were unearthed in primary data collection. The search continued until very little additional information relevant to the study was found. Only articles containing the relevant information to exogenous elements and RWHI TIS development in the study sites were selected for the analysis.

Finally, 41 semi-structured and unstructured interviews and a focus group discussion were conducted with farmers, NGO, private sector employees, public sector officials and researchers to gather more information on RWHI adoption processes and exogenous elements they believed enabled or impeded TIS function development in the study sites, and NGOs’ involvement in RWHI initiatives over the past few decades. Initial interviews with experts in this field helped in the identification of potential sites that could be focused on for this empirical study. Site visits and non-participant observation were then conducted to determine the most relevant sites. Participants were identified through snowball sampling once familiarity with each site was established. The interviews and focus group discussion were mainly carried out in English, which many people are familiar with, but those with less familiarity with English spoke in either Swahili or Akamba, which was translated for the researcher.

The study uses the method of causal process tracing to analyze information gathered from both primary and secondary sources. The analysis starts in the early 20th century after European settlers began to arrive in Kenya and exogenous elements underwent major changes, to the present day. Primary data were transcribed for analysis and used to identify exogenous elements that played a major role in shaping the development of RWHI TIS. Journal articles and academic theses were used to verify information gathered through primary data, provide greater background and context to the role of exogenous elements in RWHI TIS development, and identify gaps for further primary data collection to fill. Policy documents and project reports were screened for relevant information on agricultural development and irrigation resources. Data were then grouped into two categories for each study site: the emergence and presence of exogenous elements, and the history of the RWHI TIS development. The main exogenous elements triggering or influencing these interactions are outlined in a timeline (see Fig. 1).

[1] Based on critical realist research processes, retroduction involves moving between observable phenomena and possible explanations to gain a deeper understanding of complex reality [45].

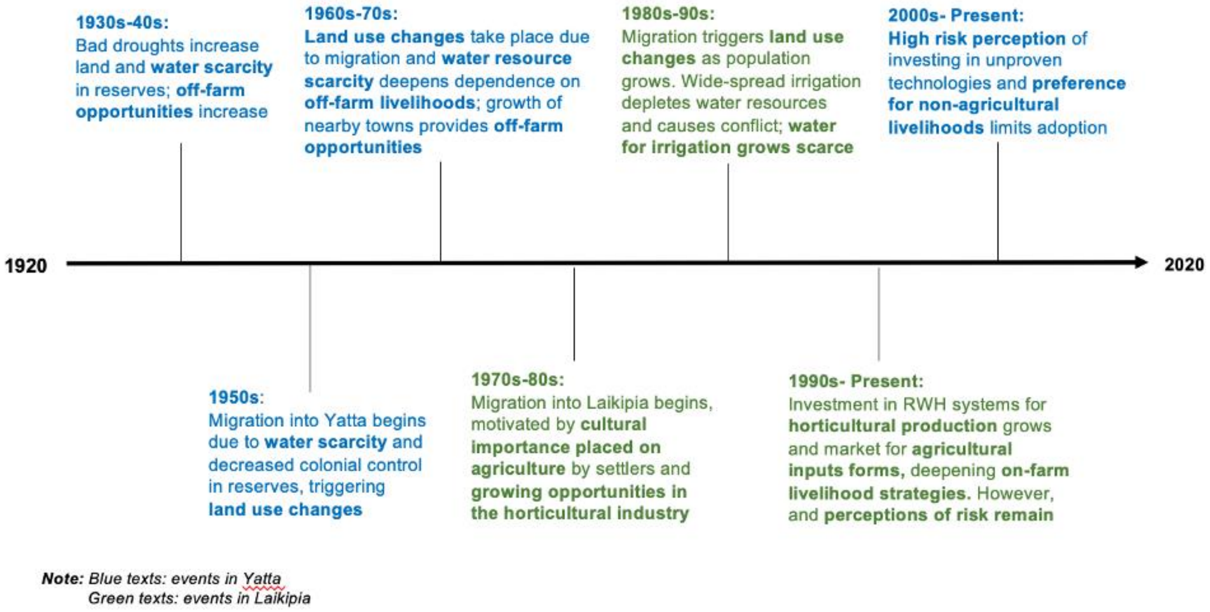

Fig. 1. ***Timeline depicting exogenous elements influencing the development of RWHI TIS functions***

4 RESULTS

The RWHI TISs in Laikipia and Yatta were analyzed to identify exogenous elements that influenced its development (see Table 1).

Table 1. Overview of exogenous elements and TIS development in Laikipia and Yatta

Exogenous elements	TIS structural elements	TIS development
LAIKIPIA		
Water resource scarcity due to population pressures and limited rainfall in a semi-arid climate	- RWHI system introduced into the region (*Artifact*) - NGOs and government agencies encouraged farmers to look for ways to irrigate crops through RWHI *(Actors and artifact)* - Water scarcity prompted the creation of WRUAs to manage water conflicts and policy measures to encourage RWHI *(Institutions)* - Networks of private, public, academic, and NGOs created to collaborate on RWHI (*Interactions*) - Knowledge-based and financial infrastructure developed to support RWHI *(Infrastructure)*	- Formation of knowledge development function [*F2*] due to introduction of RWHI - Formation of knowledge diffusion function [*F3*] as interactions between actor-networks deepen - Formation of guidance of search function [*F4*] due to potential of RWHI to solve water scarcity issue - Formation of resource mobilization function [*F6*] due to support from actor-networks
Land use changes due to land reform, large-scale migration, and increased agricultural production	- Land use changes propelled adoption of agricultural intensification practices including RWHI (*Institutions*) - Cooperatives and farmer groups formed that exchange information about RWHI practices and technologies (*Actors and interactions*) - Knowledge-based infrastructure created to improve on RWHI system design (*Infrastructure*) - RWHI system design adapted to local context (*Artifact*)	- Growth of knowledge development [*F2*], knowledge diffusion [*F3*], guidance of search [*F4*] and resource mobilization [*F6*] functions due to deepening support by actor-networks, increased interactions between them, the creation of relevant infrastructure, and improved RWHI system design - Formation of creation of legitimacy function [*F7*] as more farmers adopt RWHI

Horticultural industry development due to political support and economic opportunities	- Output markets and buyers for irrigated vegetable products are established (*Actors*) - Policies require RWHI for large-scale commercial farms (*Institutions*) - Informal and formal networks around market information and credit provision enable investment in RWHI (*Interactions*) - Roads, ICT and air infrastructure development for the horticultural industry connects the region to Nairobi, enabling RWHI diffusion and increasing exports of irrigated horticultural products (*Infrastructure*) - Improved RWHI design due to adoption and investment by horticultural industry (*Artifact*)	- Growth of knowledge development [*F2*], knowledge diffusion [*F3*], guidance of search [*F4*] and resource mobilization [F6] due to horticultural industry's support & use of RWHI - Formation of entrepreneurial activities function [*F1*] as actors begin supplying RWHI technologies suited to farmer needs - Formation of market formation function [*F5*] as institutions, interactions and infrastructure make RWHI systems more accessible
Agricultural input market formation due to horticultural industry development	- Sellers of agricultural inputs complementing RWHI systems and improving the system's performance are established in region (*Actors and artifact*) - Increased awareness of inputs necessary to maximize potential of irrigation through RWHI (*Institutions*) - Informal and formal networks around market information and credit provision enabled investment in RWHI (*Interactions*) - Physical, financial, and knowledge-based infrastructure development supports farmers' adoption process of RWHI (*Infrastructure*)	- Growth of entrepreneurial activities [*F1*], knowledge development [*F2*], knowledge diffusion [*F3*], guidance of search [*F4*], market formation [*F5*], and resource mobilization [*F6*] functions as other inputs maximizing the potential of RWHI become known, available, and accessible - Growth of creation of legitimacy function [*F7*] as RWHI adoption becomes more viable and profitable
Household characteristics including livelihood strategies, risk perceptions and cultural values and preferences	- Livelihood strategies based on deepening on-farm investment increases potential for RWHI adoption (*Institutions*) - High risk perceptions of new technologies and artifacts decrease investment in RWHI (*Institutions*) - Cultural values and preferences emphasizing the role of agriculture (*Institutions*)	- Growth of creation of legitimacy function [*F7*] as RWHI adoption aligns with livelihood strategies and cultural values and preferences - Stagnation of resource mobilization function [*F6*] due to limited capacity/desire for riskier investments
YATTA		
Water resource scarcity due to population pressures and limited rainfall in semi-arid climate	- RWHI system introduced into the region (*Artifact*) - NGOs and government agencies encouraged farmers to look for ways to irrigate crops through RWHI *(Actors and artifact)* - Networks of private, public, academic, and NGOs created to collaborate on RWHI (*Interactions*) - Knowledge-based and financial infrastructure developed to support RWHI *(Infrastructure)*	- Formation of knowledge development function [*F2*] due to introduction of RWHI - Formation of knowledge diffusion function [*F3*] as interactions between actor-networks deepen - Formation of guidance of search function [*F4*] due to potential of RWHI to solve water scarcity issue - Formation of resource mobilization function [*F6*] due to support from actor-networks
Land use changes due to land reform, large scale migration and increased agricultural production	- Land use changes propelled adoption of agricultural intensification practices including RWHI (*Institutions*) - Cooperatives and farmer groups formed that exchange information about RWHI practices and technologies (*Actors and interactions*) - Knowledge-based infrastructure created to improve on RWHI system design (*Infrastructure*) - RWHI system design adapted to local context (*Artifact*)	- Growth of knowledge development [*F2*], knowledge diffusion [*F3*], guidance of search [*F4*] and resource mobilization [*F6*] functions due to deepening support by actor-networks, increased interactions between them, and creation of relevant infrastructure - Formation of creation of legitimacy function [*F7*] as some farmers adopt RWHI

Growth of off-farm opportunities due to economic opportunities in nearby urban areas	- Dominant support is for subsistence production, limiting commercial scope and household investment in RWHI (*Actors and institutions*) - Limited informal and formal networks around market information and credit provision for RWHI (*Interactions*) - Roads and ICT development to facilitate out-migration and off-farm incomes (*Infrastructure*) - Inappropriate design and limited technologies available for augmenting RWHI system (*Artifact*)	- Stagnation of growth of knowledge development [*F2*], knowledge diffusion [*F3*], guidance of search [*F4*] and resource mobilization [*F6*] functions due to limited growth of agricultural and horticultural industries
Household characteristics including livelihood strategies, risk perceptions and cultural values and preferences	- Livelihood strategies based on deepening off-farm investment decreases capacity, desire or need for RWHI adoption (*Actors and institutions*) - High risk perceptions of new technologies and artifacts decrease investment in RWHI (*Institutions and artifact*) - Cultural values and preferences do not prioritize agricultural production (*Institutions*)	- Decline of creation of legitimacy function [*F7*] as RWHI adoption does not align with livelihood strategies and cultural values and preferences - Stagnation of resource mobilization function [*F6*] due to limited capacity/desire for riskier investments

4.1 Development In RWHI TIS In Laikipia

4.1.1 Exogenous Elements Trigger The Formation Of RWHI TIS

Beginning from the early 20th century until the present day, exogenous elements gave rise to conditions that prompted the formation of a RWHI TIS. During the colonial period, Laikipia was part of the so-called “White Highlands”, or areas exclusively allocated for British settlement. After independence in 1963, most settlers sold their land back to the government and left the country. In the 1980s, the horticultural boom, accompanied by rising prices and foreign demand for vegetables, fruits, and flowers, drove migration into Laikipia. Large numbers of people began to settle permanently, hoping to work for large horticultural farms, become outgrowers for them, or sell to the market themselves [46, 47]. Most of the migrants came from the neighboring Gikuyuland, one of the former African reserves. The promise of land ownership was a major pull factor as land is important for social and economic status in Kikuyu culture. The Kikuyu have traditionally relied on rainfed agriculture for their livelihoods, and the type of smallholder agriculture they practiced was developed in the wetter regions that migrants were coming from [48]. Laikipia underwent major land use changes as ranches were transformed into smallholder farms [47].

While rainfall levels vary across the semi-arid Laikipia plateau, parts of it are relatively well-watered and receive 600-1,100 mm of rainfall a year [49]. However, the rapidly rising population in Laikipia led to an increased demand for water for both domestic and irrigation purposes, and the region’s limited water resources now had to be shared between pastoralists, smallholders, and large-scale horticultural farmers. Even though Laikipia has the hydrological advantage of having several mountain streams and rivers due to its proximity to Mt. Kenya, the dramatic rise in population post-independence placed enormous pressure on surface water resources. Low levels of rainfall and frequent dry spells aggravated the situation, and there was often insufficient water for household needs [48, 50, 51]. The growing water scarcity and resulting food insecurity led to efforts in the late 1980s by the Anglican Church of Kenya to construct reservoirs that would collect and store run-off after rainfall. This marked the beginning of RWHI adoption in Laikipia and the formation of endogenous structural elements.

By the 1990s, Water Resource Users Associations (WRUAs) were established and tasked with fairly allocating surface water resources for domestic uses [52]. As smallholder households became increasingly assured of basic water security, they were more willing to spend their incomes on non-subsistence activities and people were able to consider larger and riskier agricultural investments to improve their livelihoods [48, 53]. However, the frequent intervening dry spells and WRUA restrictions on water use made it difficult for smallholders to sustain horticultural production. Reluctant to give up opportunities provided by the growing horticultural sector, many smallholder farmers abstracted water illegally from rivers and streams. NGOs began encouraging the adoption of household farm ponds so that harvested water could be used for subsistence agricultural production or the irrigation of small vegetable gardens and decrease pressure on other surface water resources [10, 50].

Large-scale commercial farms, meanwhile, were able to obtain legal permits to carry out abstraction. Between 1991 and 2003, 24 large horticultural farms were established in Laikipia, covering 1,085 hectares, and employing tens of thousands of people [10]. Many of these farms grew crops for exportation to the European market, although the domestic market for horticulture was also growing rapidly. In addition to hiring on-farm workers, it employed smallholder farmers as out-growers, who enjoyed subsidized provision of inputs, technical advice and support, and reliable access to output markets. Even those farmers not directly employed by the horticultural industry benefited from improved access to market information and agricultural inputs, as well as industry-driven infrastructure construction. These developments lowered transaction costs and helped farmers tap into horticultural markets as individuals or collectives [54, 46, 55].

The exogenous elements of water scarcity, land use changes, horticultural market development and agricultural input market formation gave rise to the first RWHI TIS functions. Water resource scarcity and land use changes triggered knowledge development [F2] due to the introduction of RWHI, knowledge diffusion [F3] as interactions between actor-networks involved in RWHI deepened, guidance of search [F4] due to potential of RWHI to solve water scarcity issue, and resource mobilization [F6] from the support of actor-networks for RWHI. The growth of the horticultural industry and agricultural input markets led to the creation of legitimacy [F7] as more farmers adopted RWHI, entrepreneurial activities [F1] as actors began supplying RWHI technologies suited to farmer needs, and market formation function [F5] as institutions, interactions, and infrastructure supported RWHI adoption.

4.1.2 Emergence Of Systemic Opportunities And Problems In RWHI TIS

To encourage the adoption of RWHI in the 1980s and 1990s, NGOs supported farmers with technical advice or financial assistance [10, 51]. However, seepage problems in the farm ponds severely curtailed levels of adoption, and harvested water would often not be sufficient for intended uses. Since most ponds were unlined, between 30-50% of water was lost [10]. Several problems also arose from siltation, as many ponds did not have silt traps, and high rates of evaporation, as most did not have shade nets or other means to limit evaporation. The high cost of farm pond construction and the unreliability of rainfall also dissuaded investments in RWHI systems. Many farmers that had dug farm ponds ended up abandoning them after they failed to meet their needs [56, 57], although others continued to experiment with farm ponds to maximize their water holding capacity, trying out plastic lining, bitumen lining, clay lining, and even goat trampling. However, high seepage and evaporation rates continued to limit adoption [10].

Large-scale horticultural farms in Laikipia also had to find a solution to the growing water scarcity problem if they were to continue their operations. Not only was the water in rivers and streams rapidly depleting, but the Water Act of 2002 mandated that those actors abstracting surface water for irrigation had to build flood storage infrastructure to harvest water during rainy seasons for use during the dry seasons [58]. With their access to finance and exposure to international markets, these large-scale farms were able to find a way to make water harvesting viable using ultraviolet polythene sheets, also known as dam liners. Dam liners, manufactured in Israel, resolved the seepage issues that had plagued rainwater harvesting efforts over the last few decades [10]. The introduction of dam liners drove farm ponds' uptake among smallholder farmers in Laikipia. Those farmers who were interested in growing high-value horticultural crops for the market and could afford the initial costs of dam liners (usually from off-farm income) invested in them. By dramatically reducing seepage from their farm ponds, dam liners made an investment in RWHI worthwhile. Farmers could often recover costs within a few seasons of selling their produce. Yields for those farmers that adopted RWHI were many times higher than those who did not [57]. Selling horticultural crops, either to companies or on the market, has now become a lucrative source of income for many smallholder farmers.

These developments contributed to the high level of quality and capacity of actors, institutions, interactions, infrastructure and RWHI technologies that formed the RWHI TIS, and gave rise to four systemic opportunities. Specifically, the adoption of RWHI could improve household irrigation capacity, increase water productivity, maximize the potential of other agricultural inputs, and increase household income. One systemic problem also arose, which was that the high initial investment in RWHI systems could decrease household income. Overall, the strength of the interactions between four systemic opportunities, which are linked together in a reinforcing feedback loop, helped mitigate the effect of the systemic problem. Households were able to invest in RWHI technologies and profit from their adoption.

4.1.3 RWHI TIS Development Accelerates And Begins Affecting Exogenous Elements

While there is a range of RWHI present in Laikipia, most smallholder farmers with farm ponds try to obtain a dam liner to limit seepage, a pump to draw out water, and drip kits or sprinklers to distribute water in the field. Some smallholder farmers also have tanks to store extra water, and others own shade nets or use natural vegetation to cover the pond and limit evaporation. A range of irrigation companies providing RWHI technologies and associated services have entered the market, and competition between them has resulted in a more varied and affordable supply of technologies. Some entrepreneurial farmers have formed partnerships with irrigation companies and sell advisory services to other farmers who want to adopt RWHI. Peer-to-peer learning between neighbors, friends, and farmer groups also helps encourage adoption.

Three other exogenous elements helped accelerate the development of the RWHI TIS. Livelihood strategies that prioritized the intensification of on-farm activities, and values and preferences that give a high level of importance to agricultural production, drove the creation of legitimacy function [F7]. However, perceptions that see the adoption of a new and relatively expensive technology as too risky contributed to the stagnation of resource mobilization function [F6]. Consequently, all functions grew in Laikipia, but not all have matured due to the high initial cost of RWHI and household risk perceptions. Several functions did mature enough for the focal TIS to begin affecting two exogenous elements, horticultural industry development and agricultural input market formation. The growing numbers of farmers adopting RWHI has encouraged horticultural companies to employ more smallholder out-growers, which has enabled farmers to increase investments in RWHI. Increased use of agricultural inputs by smallholder farmers adopting RWHI has created incentives for agricultural input providers to set up offices in the region to improve access to customers and sell more RWHI technologies and artifacts.

4.2 TIS Development In RWHI TIS In Yatta

4.2.1 Exogenous Elements Trigger The Formation Of RWHI TIS

In Yatta, several exogenous elements gave rise to conditions that prompted the formation of a RWHI TIS. During the colonial period, Yatta was demarcated under “Crown Lands”, or areas that the colonial administration was in full control of. The native population in Yatta, the pastoralist Akamba, were forced out into bordering reserves. The colonial administration was worried that unrestricted access by the native population would lead to soil degradation, threatening the profits that were gained from ranching there [59]. With the establishment of the Crown Lands, the Akamba lost two-thirds of their most productive grazing grounds [60]. As restrictions on movement grew, the colonial administration-imposed labor laws and taxes forced many Akamba to sell their livestock to meet their basic needs. Without their livestock, the Akamba had to find other ways to sustain their livelihoods. As was intended by the colonial administration, many turned to wage labor for European establishments, which were dependent on cheap and exploited labor for their production. Bad drought years in the 1920s hastened this turn towards wage labor and out-migration, as did the need for money in the new cash-driven economy, and there were now acute shortages of male labor in the reserves [61, 59].

Continuous droughts and a lack of water made life on the reserves increasingly untenable. As independence seemed more and more inevitable, the colonial administration began to loosen restrictions on Yatta. People began streaming into the plateau. Migration increased after independence in 1963 and continued well into the decade after it [59]. Most communities turned to agricultural production or off-farm work for income, abandoning their pastoral livelihoods, as there was little room for herds to graze [60]. However, water scarcity due to frequent droughts, limited surface water resources, ill-maintained water reservoirs, and deforestation meant food and water insecurity was common [62]. The Yatta plateau receives 600-1,100 mm of rainfall a year and has limited water resources, although the mix of clayey and loamy soils is suitable for some forms of agriculture [49, 63]. By the 1980s, most of the land was claimed, leaving little room for agricultural expansion to meet growing food demands, even as population densities kept increasing [61].

As farmers attempted to intensify production in response to shrinking land and water resources, NGOs in the area began to promote soil and water management practices. This spread knowledge and awareness amongst smallholder farmers of RWHI systems, mainly in the form of rooftop collection for domestic needs and farm ponds for irrigation. However, problems with the design of farm ponds (seepage, siltation, and evaporation) as well as high investment costs meant that most farmers were reluctant to invest in RWHI systems [10]. Instead, to meet their subsistence needs, many households intensified their off-farm activities so that money earned could be used to buy food off the market. Infrastructure development that started during the colonial period helped facilitate seasonal migration to the rapidly growing towns of Kitui and Machakos, as well as Nairobi. Rainwater harvesting, if present, was limited to rooftop collection to meet household needs [61, 62, 64]. Consequently, the quality and capacity of endogenous structural elements was limited and only five TIS functions formed. These include knowledge development [F2], knowledge diffusion [F3], guidance of search [F4] resource mobilization [F6], and creation of legitimacy [F7] functions.

4.2.2 Emergence Of A Systemic Opportunity And Problems In RWHI TIS

Farmers in Yatta do not have a well-established and easily accessible output market where they can sell their produce. Due to the presence of relatively few surface water bodies, output markets for horticultural crops are mainly limited to meeting demand from nearby market towns. Agricultural input providers, including those that supply RWHI technologies, do not have a strong presence. Most agriculture in Yatta continues to depend on traditional farm implements such as hoes; the low levels of mechanization in the area are indicative of low levels of farm productivity [65]. The input market for RWHI technologies is driven primarily by NGOs and occasionally government agencies that mass-order dam liners, all of one size and type, and has not developed to respond to a range of individual farmer needs. Most companies do not have many branches in the area, making it difficult for farmers to reach out to them on their own [64]. The lack of well-developed and responsive input and output markets for RWHI technologies has contributed to limited RWHI adoption.

Most smallholder farmers that have adopted RWHI use only a limited number of technologies. While many farmers have lined their farm ponds (largely through NGO assistance), the lining is often of concrete, which quickly develops cracks, or sub-par dam liners, which do not last long. The design of farm ponds is usually determined by NGOs and standardized for all beneficiaries, regardless of differences in intended uses of the water. A few farmers have treadle pumps to draw water out of the pond, and a very small number are using drip kits and extra water tanks, but the majority extract and distribute water manually with buckets. Many household ponds are a simple, unmeasured a hole in the ground. Households are not very keen to invest their own money in upgrading their farm pond, mainly because agricultural production in Yatta is not very profitable.

The exogenous elements of water resource scarcity and land use changes engendered the development of the first endogenous structural elements of the RWHI TIS. As the quality and capacity of the endogenous elements improved due to support by actor-networks, increased interactions between them, and the creation of relevant infrastructure, two systemic opportunities– that RWHI could improve household irrigation capacity and maximize water productivity– arose. However, one systemic problem, that investing in RWHI can limit returns from other livelihood strategies, also developed due to the limited growth of agricultural and horticultural industries in the region. Since investment in RWHI does not increase overall household income, TIS development is limited.

4.2.3 RWHI TIS Development Stagnates And Does Not Affect Exogenous Elements

Although farm ponds are present in Yatta, they are built largely with the financial and technical support of NGOs, who often partner with government bodies. They are usually basic systems that can only supply enough water for domestic needs and kitchen gardens. Household water insecurity still affects much of the population. The main sources of water are borewells, many of which have run dry or drawn low-quality water, and reservoirs, where water is shared with livestock. While there are some rivers, few are perennial, and people are forced to dig a few feet into the riverbed to get some water during the dry months. In some areas, women still walk up to six kilometers to fetch water during the dry season [65, 66]. Since this work falls mainly on women, NGOs have geared most of their RWHI projects to appeal to women self-help groups, and doggedly promote farm ponds as a way for households to meet both their subsistence needs and a grow little extra for the market. However, household water insecurity has contributed to a reluctance to invest in expensive RWHI technologies that largely only help save, rather than generate, income.

Moreover, as NGO workers observed, women often have less decision-making power in their household and are unable to make investments in improving and maintaining their farm ponds. Men tend to dismiss RWHI systems as useful only for subsistence production and, knowing less about potential commercial uses, are unwilling to make investments in it [67, 68]. They are instead more likely to invest in what they deem to be less risky, off-farm activities. Even in 1994, off-farm opportunities were seen as a “much more profitable use of their time than producing unsaleable food crops” [61]. In fact, as more and more people migrated out of Yatta, labor to work on farms grew increasingly scarce and profitable agricultural production became even harder [64]. Ultimately, three exogenous elements– cultural values and preferences, risk perceptions, and livelihood strategies– slowed overall TIS development. They contributed to the decline of creation of legitimacy function [F7], as RWHI adoption does not align with livelihood strategies and cultural values and preferences, and the stagnation of the resource mobilization function [F6], due to limited household capacity/desire for riskier investments.

5 Discussion

Exogenous elements give rise to conditions that create a need for a particular innovation. The explicit analysis on the presence and nature of exogenous elements helps draw out reasons behind TIS formation and growth [69, 26, 70]. In this case, exogenous elements gave rise to new challenges that actors (NGOs) responded to by introducing new technological artifacts (RWHI). As Geels and Schot (2007) observe, exogenous elements do not mechanically lead to TIS formation but instead need to be perceived and translated by actors [27]. Land and water scarcity, combined with land use changes, prompted the formation of the TIS functions of knowledge development [F2], knowledge diffusion [F3], guidance of the search [F4] and resource mobilization [F6] in both Laikipia and Yatta. This demonstrates that certain ecological conditions created an enabling environment for RWHI TIS. The likelihood of RWHI TIS formation is higher in semi-arid areas without enough perennial surface water resources to last through the dry season, but with enough rainfall to increase water security if harvested.

In addition to triggering the formation of a TIS, exogenous elements can also affect the capacity or quality of its endogenous structural elements and give rise to systemic problems or opportunities within the TIS. A systemic problem slows the development of a TIS because of the low quality/capacity of endogenous structural elements. A systemic opportunity is the outcome of high quality/capacity of endogenous structural elements within a TIS and accelerates TIS development [36, 27, 72]. In Laikipia, systemic opportunities were that RWHI could improve household irrigation capacity, increase water productivity, maximize the potential of other agricultural inputs, and increase household income. They were able to mitigate the systemic problem of the high initial investment in RWHI systems. Many households were able to invest in RWHI technologies and earn relatively higher incomes, compared to other livelihood strategies. In Yatta, two systemic opportunities– that RWHI could improve household irrigation capacity and maximize water productivity– could not outweigh the major systemic problem, that investing in RWHI can limit returns from other livelihood strategies. Since investment in RWHI does not increase overall household income in Yatta, TIS development is limited. Therefore, while TIS development in Laikipia accelerated due to systemic opportunities, TIS development in Yatta stagnated due to its systemic problems.

In Laikipia, the RWHI TIS reached a level of maturity that enabled it to “structurally couple” with and begin affecting exogenous elements in a bi-directional relationship. This has the effect of embedding the TIS within its context and can give rise to properties of path-dependence and resilience that further accelerate TIS development. In Laikipia, for example, the RWHI TIS is structurally coupled with two mature and quickly growing sectoral innovation systems: the horticultural industry and the agricultural input market. As the RWHI TIS grew, actors within the horticultural industry and agricultural input market participated in the development of the TIS by aligning their needs and technological trajectories and even co-creating solutions. These structural couplings facilitated the flow of assets between exogenous and endogenous elements and created common institutions, reinforcing their growth. Although structural couplings are rare in the early phases of TIS formation, they are necessary for a new technology or technological artifact to become embedded in its wider context [22, 27].

In Laikipia, favorable exogenous elements, including the development of a horticultural industry and agricultural input markets, helped support an enabling environment the continued growth of the TIS. In Yatta, however, unfavorable exogenous elements meant that investment was often directed away from on-farm activities, which led to stagnation of several TIS functions. The household livelihood strategies that households chose to pursue were also heavily influenced by socioeconomic and cultural institutions and norms around on-farm investment. This suggests that policies or strategies aimed at encouraging the adoption of RWHI should identify conditions in the wider enabling environment that can contribute to the growth of the RWHI TIS without requiring constant external assistance. In this case, RWHI TIS growth only took place where input and output markets are sufficiently present and investment in RWHI was aligned with households’ primary livelihood strategies. Policy or governance interventions could also benefit from identifying and building upon existing systemic opportunities when promoting RWHI [72]. Identifying feedback loops between systemic problems or opportunities can also help policy makers or development actors concentrate and target their resources to maximize efforts [73].

6 CONCLUSION

This article used the lens of technological innovation systems (TIS) to analyze the role of exogenous elements in creating an enabling environment for rainwater harvesting for irrigation (RWHI) TIS development [26, 69, 22, 27]. The case of RWHI in Kenya demonstrates that exogenous elements play a central role in the formation, growth and maturity of a TIS. Exogenous elements can shape the capacity and quality of endogenous TIS elements, give rise to systemic problems or opportunities within the TIS, and either accelerate or slow down overall TIS development. Findings indicate that environmental, historical, cultural, economic, and political factors must be considered when seeking explanation for the adoption or non-adoption of technologies or technological artifacts.

By making the role of exogenous elements more explicit, this article helps ascertain the potential for scaling RWHI in a specific context and determine the strength or influence of different exogenous elements on TIS development. Critically reflecting on the methods used in this study, the emphasis on qualitative data could preclude analysis of the precise dimensions of relevant exogenous elements to RWHI that can only be identified through quantitative data collection. However, this article only aims to show some examples of how exogenous elements shape RWHI TIS development, rather than unequivocally prove their exact nature. Future research could include analysis on how RWHI TIS functions are affected by the TISs of other technologies or artifacts in the agricultural and irrigation sectors in Kenya.

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