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A multi-dimensional framework for responsible and socially inclusive digital innovation in food, water, and land systems

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Abstract
Digital innovations can offer solutions to various food, water, and land systems challenges globally. However, there are concerns on the ethical and social inclusivity aspects of these innovations, particularly for marginalized groups of people in less industrialised countries. In this article, we describe the design and development of a digital inclusivity framework, which builds from a detailed synthesis of inclusivity in digital literature. Key insights from the review were collated into five dimensions: risk mitigation, accessibility, usability, benefits, and participation. These dimensions can be assessed by means of twenty-one concrete and measurable sub indicators. Our focus was to enable a more holistic approach to the usually technocentric design of digital innovations. The framework, including the associated indicators, lays the groundwork for the development of a digital inclusivity index, a tool for assessing and fostering the inclusivity of digital innovations in food, water, and land systems.

Keywords ICT for development · Inclusive innovation · Water · Natural resource management · Fourth industrial revolution · Food systems

Introduction

The production and distribution of food depends on the availability of natural resources, particularly water and land (Chen et al. 2018; Fitton et al. 2019). This is especially true in less industrialized agrarian-based countries where agricultural expansion is a key component of socio-economic development and often puts pressure on water and land resources (Kumar et al. 2012; Barbier 2020). For instance, agriculture uses more than seventy percent of all freshwater withdrawals in agrarian-based countries and agricultural expansion has been identified as the biggest contributor to the degradation of forested lands (Chen et al. 2018; Fitton et al. 2019; Barbier 2020). Within countries, areas that have large arable land, but less water availability often face higher strains on their water resources due to agricultural expansion (Kumar et al. 2012). As a result of these interlinkages, the management and governance of food systems require a coordinated and integrated approach that closely examines the relationships between food, water, and land (Ringler et al. 2013; Chen et al. 2018; Karabulut et al. 2018). In the remainder of this paper, we refer to the food, water, and land (FWL) system as the collection of actors, activities and institutions involved in food production, distribution, and consumption, as well as in the management and use of water and land resources linked to the food system.

Innovation, which includes the application of new or modified technologies, skills, and social arrangements, has been instrumental in solving some of the key challenges facing FWL systems (Pigford et al. 2018; Sixt et al. 2018;

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Uhlenbrook et al. 2022). More recently, a range of digital innovations have been experimented with and applied across FWL systems (Lele and Goswami 2017; Lim et al. 2021; Kotir et al. 2024). First, simple tools and services such as SMS, phone calls, and interactive voice responsive been applied to facilitate information access for local communities, smallholder farmers, and water user associations (Onsongo and Schot 2017; Daum et al. 2022). Second, more advanced digital innovations such as smartphone applications, e-learning platforms, and websites offer more specialized solutions such as disease identification and virtual co-learning spaces for different actors (Klerkx et al. 2019; Panganiban 2019). Third, sophisticated digital innovations such as sensors, robots, computer simulations, geographic information systems, and artificial intelligence are experimented with and applied for precision, substitution of human labor, and decision support in FWL systems (Lele and Goswami 2017; Kudama et al. 2021; Daum et al. 2022).

While digital innovations are promising as suitable tools to address some of the key challenges facing FWL systems, social exclusion and inequality remain key components of these systems, especially in the context of less industrialised countries. For instance, there is an uneven concentration of people with low incomes in remote and less favored lands who are often either excluded from official development planning or negatively impacted by it (Fitton et al. 2019; Barbier 2020). Nhamo et al. (2022) also point out that due to historical injustices such as exclusionary colonial policies, water, and land, which are critical resources for agriculture, are often unfairly and evenly distributed. In addition, specific groups of people such as women may be excluded from ownership of resources and from decision making processes in the management and governance of FWL systems (Duguma et al. 2022; Elias et al. 2023). There is therefore a risk that the development and use of digital innovations in FWL systems may either replicate these pre-existing inequalities or introduce new threats and inequalities. It is imperative to assess, guide, and monitor the development and use of digital innovation to ensure that the process and outcomes are responsible and fair for all actors involved in FWL systems, particularly marginalized communities in rural areas. A framework with metrics for such a process currently lacks within policy and academic debates on digital inclusivity in the FWL systems of less industrialised countries.

The aim of this article is therefore to develop such a normative framework, with tangible metrics and indicators for assessing and promoting digital inclusivity, through a critical and interpretive synthesis of peer reviewed studies as well as grey literature. In the next section, we discuss current theoretical perspectives on inclusive, just, and responsible innovation. We then present the methodological approach to the literature synthesis. This is followed by a presentation of our findings. We conclude the article with a discussion of the implications of our findings for research, policy, and practice on digital inclusivity.

Current theoretical perspectives on inclusive and responsible innovation

There are competing normative interpretations and assumptions from different strands of literature concerning what constitutes a just, responsible, or socially inclusive innovation process (Pansera 2014; Levidow and Papaioannou 2018; Opola et al. 2021). Rooted in the adoption and diffusion of innovations theory (Rogers 1995), the first strand of literature examines the technical, socio-cultural, and economic factors that lead to faster and higher rates of adoption of technologies by some actors and slower rates and extent of adoption by others. In digital innovation for instance, addressing the divides between people and regions that have access to digital technologies and services and those that do not is considered a key component of just and socially inclusive innovation processes (Upadhyaya et al. 2019; Vassilakopoulou and Hustad 2021; Zheng and Walsham 2021). In particular, people living in marginalized rural areas, smallholder farmers, people with little formal education and skills, and people living with disabilities are cited as groups that often face barriers to accessing and using digital technologies (Molina-Maturano et al. 2022; Porciello et al. 2022; McGrath et al. 2023). Women may also face additional barriers due to pre-existing exclusionary sociocultural norms in what has been described as the gender digital divide (Hilbert 2011; Mukherjee et al. 2024). Inclusivity according to this paradigm refers to approaches and interventions that bridge these divides by making technologies, skills, and services available, accessible, and usable to marginalized groups of people (Banerjee 2005).

The second interpretation on social inclusivity stems from the academic debate on participation (or lack thereof) of marginalized groups of people in innovation processes, not necessarily only digital ones. Most of this literature is inspired by the Arnstein Ladder of Citizen Participation, which outlined various levels through which urban residents can participate in planned development (Arnstein 1969). The extent of participation ranges from being informed and consulted at lower rungs of the ladder to being partners and co-designers of development projects at highest rungs. This paradigm influenced participatory research and development approaches in the 1990s where the participation of local communities in research, management, and development of agriculture, water, land, forests, and other resources was considered a critical component of ethical and inclusive

development processes (Chambers 1994; Telleria 2020). In digital innovation, approaches such as citizen science have been recommended as ways to include the knowledge, skills, and perspectives of rural communities, smallholder farmers, and rural water associations in digital innovations such as land mapping, modelling, and digital agricultural services (Songok et al. 2011; Radjawali et al. 2017; Nyadzi et al. 2020; Peddi et al. 2023).

Third, and more recently, conceptualization of just innovation has focused on ethical and responsible innovation processes in FWL systems (Stilgoe et al. 2013; Von Schomberg 2014; van der Burg et al. 2019; Ludwig and Macnaghten 2020). With the advent and deployment of sophisticated technological applications, including genetic innovation, digital technologies, and nano technology, there have been concerns over the potential negative impacts of such innovations to society in general. Inclusivity, here defined as the provision of opportunities for stakeholders with differing concerns and viewpoints to collaborate through dialogue and deliberation, is one among four dimensions of the AIRR (anticipation, inclusion, reflexivity, responsiveness) framework of responsible research and innovation. Together with anticipation, defined as the definition of scenarios for consequences, reflexivity, the reflection on the activities and assumptions that govern science and innovation, and responsiveness, the adaptation to demands of stakeholders and the environment, inclusivity is one pillar of this approach (Stilgoe et al. 2013).

Each of these three paradigms on inclusive and responsible innovations have limitations. The innovation diffusion paradigm has been criticized for being too technocentric and relying on a linear model of innovation with innovators on the one hand, and adopters on the other without an explicit analysis of the interactions between the two (Pant 2019; Mahlangu et al. 2022; Touri 2024). The participation paradigms, on the other hand, have been criticized for emphasizing participation as an end goal and for failing to consider the social contexts and structures within which participation can be enabled or disabled (Collins and Ison 2009; Botchwey et al. 2019; Laskey and Nicholls 2019; Heeks 2022). The responsible research and innovation framework has been criticized for its lack of operationalization and measurability (Nordmann 2014; Von Schomberg 2014) and its focus on (Western) normative considerations (Stilgoe et al. 2013; McCampbell et al. 2022). Given these limitations, there is a need for a holistic set of metrics for digital inclusivity, focused on digital innovation in the FWL systems of less industrialised countries (Lajoie-O'Malley et al. 2020; Iazzolino and Stremlau 2024; Steinke et al. 2024). The objective of this paper is therefore to develop a comprehensive framework, with a set of tangible indicators, for assessing and promoting responsible and socially inclusive development and application of digital innovations in the FWL systems of less industrialised countries. The central question that the article addresses is:

- What characterizes a just and socially inclusive digital innovation process in the food, water, and land systems of less industrialised countries?

Such a framework can be instrumental in solving the various contradictions that exist between different policy actors and academic disciplines on what constitutes a socially inclusive digital innovation process (Béné et al. 2019; Lioutas et al. 2021) thereby providing a standard guideline and avenues for collaboration. A holistic framework with a clear set of indicators can also be a valuable tool for assessing and promoting responsible, ethical, and socially inclusive digital innovation as proposed by Lajoie-O'Malley et al. (2020). We focus on less industrialized countries because most of their population is directly dependent on FWL systems for their livelihoods (Juma 2011; Pigford et al. 2018), and the application of digital innovation is likely to have a greater economic, social, and cultural impact in these regions.

Rather than focus on a specific set of marginalized groups of people, we adopt an intersectional approach, that simultaneously addresses the challenges faced by people with low incomes, minimal formal education, elderly people, people living with disabilities, marginalized women, and other groups of people that are excluded from, or likely to be negatively impacted by digital innovation. While we acknowledge that each of these groups of people have unique challenges that warrant specific attention, people are likely to belong to more than one category of marginalization (Hankivsky et al. 2014; Kwan 2023; Zheng and Walsham 2021). For the remainder of the paper, we used the term 'marginalized groups' to refer to people within FWL systems that are vulnerable due to low wealth status, and face further marginalization due to their geographical status, education status, age, gender, social status, or physical disability. We also use the term 'digital inclusivity' to refer to just, responsible, and socially inclusive development and deployment of digital innovations. This broader perspective extends beyond inclusion in the use and benefit of digital tools and services to encompass the terms of inclusion, consequences of inclusion, and any potential risks introduced by inclusion in the use and benefits of digital innovations. In the section below, we describe critical interpretive synthesis, the methodological approach that we adopted to address our research objective.

Methodology

Our methodology is based on a critical review and synthesis of peer-reviewed literature, as well grey literature on digital inclusivity in FWL systems of less industrialized countries. This interpretive approach to reviewing and synthesizing literature was selected because the overall aim was to develop a framework on digital inclusivity rather than aggregate and summarize all the literature on the topic. Sampling of literature was mainly based on theoretical sampling, while analysis was primarily inductive, using the themes and concepts that emerged from the literature synthesis to build a framework and indicators of digital inclusivity.

Critical interpretive synthesis

Critical interpretive synthesis (CIS) is one of the methods used for a qualitative review and synthesis of literature (Booth et al. 2016; K Flemming et al. 2019). It uses analytical techniques borrowed from primary qualitative research (Depraetere et al. 2021). The methodology has three key aspects. First, it employs a critical scrutiny of a variety of types of literature sources, with quality checks being based on the credibility and relevance of the evidence provided from each source in contributing to the theme being explored, rather than on the research methods used (Dixon-Woods et al. 2006). Second, the methodology is interpretive, meaning that it seeks to explain complex phenomena (such as the development and use of digital tools and services in FWL systems) by examining and interpreting firsthand experiences, behaviors, attitudes, beliefs, and social contexts presented in multiple sources of evidence (Booth et al. 2016). Third, the methodology is a synthesis that seeks to bring together multiple viewpoints, some of which might be contradictory, to explain why and how an intervention could work. In the process, the synthesis of the diverse sources of evidence produces an explanation that is greater than the sum of all the individual sources (Kate Flemming et al. 2019).

We employ this approach because the literature on digital inclusivity in FWL systems is large, diverse, and incompatible, with different study designs and contexts being employed (Van Dijk and Hacker 2003; Lythreatis et al. 2022). In such instances, approaches that interpret and synthesize existing evidence are more suitable compared to strategies that pool together and summarize all the literature on the topic (Noblit and Hare 1999; Dixon-Woods et al. 2006). In addition, our study is motivated by the need to develop a theory or framework that explains how and why interventions on digital inclusivity could work rather than presenting evidence on what works. This objective is best obtained through a critical exploration of existing literature, a process which other methods of literature review cannot sufficiently address (Strauss and Corbin 1990; Thorne et al. 2004; Dixon-Woods et al. 2006).

Sampling and analysis of literature

As proposed by Booth et al. (2019), we started with a broad research question which functioned as a compass for the search and analysis of literature and become clearer and refined as we examined, analyzed, and interpreted new evidence. This method of sampling is referred to as theoretical sampling and mirrors methods used in primary qualitative research methods, particularly grounded theory (Strauss and Corbin 1990; Depraetere et al. 2021). It entails 'browsing and berry picking' of literature rather than following a linear and structured approach (Bates 1989). The search for new literature ended when two or more subsequent sources of new evidence did not generate any novel insights into the theories and concepts that had emerged (Strauss and Corbin 1990; Kate Flemming et al. 2019). While the CIS methodology does not follow a structured approach to identifying and analyzing literature, starting with such an approach can provide an important starting point for identifying the key themes to explore with additional evidence (Kate Flemming et al. 2019). Our search for literature therefore started in formal databases, particularly ProQuest, Scopus, Google Scholar, and the International Water Management Institute (IWMI) with the assistance of IWMI library services. Our search was limited to peer reviewed articles, government and multi-government agency reports, books and book chapters, and project reports. We also focused on literature that addressed responsible and socially inclusive digital innovation with FWL systems in less industrialised countries.

The following search terms were employed in the initial structured inquiry: (((digital OR ICT)AND (food OR agriculture OR water)) AND ((“global south” OR “developing country*”))) AND (divide OR unequal* OR inequit* OR inclus* OR innovat* OR “citizen science” OR rights OR justice OR (digital AND gender). This generated eighty-one sources across the four databases. These were all scanned and, and the twelve most relevant were read in detail, summarized in an Excel sheet, and analyzed to refine the research question. Additional literature was selected by integrating three new search strategies (Bates 1989; Kate Flemming et al. 2019): snowballing: selection of key references used or suggested in our literature sources, hand picking: browsing of specific sources such as key websites or journals for relevant articles and reports), and expert consultation: use of sources recommended by researchers and other specialists on digital inclusivity. We also expanded our database to include websites and databases of organisations such as the Food and Agriculture Organisation, World Bank,

and CGIAR. The additional literature was selected based on their relevance to the constructs and themes that were emerging from the analysis. The search for new evidence ended when three new sources of literature were analyzed but did not generate any new insights in the lines of argument that had been developed (Strauss and Corbin 1990; Depraetere et al. 2021). Ultimately, we included a total of nighty-one sources of literature published between 2003 and 2024. This dataset is composed of sixty-eight peer-reviewed journal articles, eight books and book chapters, eight project reports and seven government and multi-government policy documents.

Our analysis proceeded through two major strategies: refutational synthesis and lines of argument synthesis (Noblit and Hare 1999; Dixon-Woods et al. 2006).

Refutational synthesis

This involved a critical examination of all the evidence used in the study, including consideration of flaws and contradictions between separate studies. Contradictions between papers were characterized and attempts made to explain them. We began by summarizing the theoretical frameworks, findings, and conclusions from the studies identified in the initial structured search for literature. These summaries were presented to the broader team of authors, as well as other experts in the field to discuss contradictions and flaws between separate studies as well as credibility of the evidence in contributing to emerging themes and concepts on digital inclusivity. These discussions were conducted through shared word documents and bi-monthly virtual meetings among the authors as well as other specialists on digital inclusivity.

Lines of argument synthesis

This involved building new theories and concepts that are grounded in the findings of the individual sources of evidence. New and emerging concepts were constantly compared to new evidence, and concepts that were not supported by evidence were discarded (Noblit and Hare 1999; Dixon-Woods et al. 2006). In the end we created third order constructs (integrated evidence across the different studies into a coherent framework) from second order constructs (Findings and interpretations of the individual studies and reports included in the review). The second order constructs were in turn created from first order constructs (everyday realities and perspectives of people). In the section below, we present the findings, which are the third order constructs from our analysis on what characterises digital inclusivity in the FWL systems of less industrialised countries.

Findings

Themes and concepts emerging from the literature clustered around five key dimensions of digital inclusivity: accessibility, usability, benefits, participation, and risk mitigation. The 'accessibility' dimension refers to whether digital innovation packages, including digital infrastructure, are available and affordable for marginalized groups. The 'usability' dimension concerns whether marginalized groups have the skills to make use of the digital innovation. Beyond access and use, the 'benefits' dimension refers to the practical value of digital innovation to the day-to-day lives of marginalized groups. The 'participation' dimension relates to the extent to which marginalized groups can contribute to the development, governance, and discourses on the digital innovation. Finally, the 'risk mitigation' dimension examines the ethical and socio-political aspects of digital innovation. A set of twenty-one concrete indicators that help to define and measure success in digital inclusivity across the five dimensions were also elicited from the literature. In the next section, we present and describe the various indicators under each of the five dimensions.

Dimensions and indicators of digital inclusivity

Accessibility to digital innovations

A number of authors have pointed out that public and private investments in digital innovation often sideline regions or people that pose greater risks and offer little returns on investment (e.g. Michael et al. 2019; Abdulai and Fraser 2022). As a result, some people are excluded from access to digital technologies and services, especially in the remote areas of less industrialized countries (Aissaoui, 2022; Lythreatis et al. 2022). For instance, some communities often face deficient or unreliable digital infrastructures such as internet and mobile connectivity, which exclude them from accessing services such as digital extension services or climate forecasts (Deichmann et al. 2016; Aissaoui 2022; Zheng and Walsham 2021). Even if such services and technologies are available, people with minimal wealth may not afford to buy, continuously use, or extract value from such technologies and services. (Tsan Michael et al. 2019; Abdulai et al. 2022; Hernandez et al. 2024). Rotz et al. (2019) recommend the targeting of large-scale public digital infrastructure projects to areas and communities that are neglected or risky, such as remote areas as an approach to foster digital inclusivity. Alternatively, digital innovation packages can be developed to be compatible with the pre-existing digital infrastructure in areas where marginalized groups of people live.

Besides the availability and affordability of digital innovations, there are people who might not be aware of the range of digital tools and services available, as well as the benefits that can be derived from them. Based on an empirical study conducted in Kenya, Kieti et al. (2022) argue that one of the reasons for the low adoption rates of digital agricultural advisory services by smallholder farmers in Kenya is the use of digital platforms to create awareness on such services rather than through channels that are preferred and accessible to smallholder farmers such as radio, TV, and face to face interactions. Smith and Lie (2023) also point out that there is often a gap between the way digital technologies and services are designed and the use habits, routines, and preferences of marginalized groups of people such as smallholder farmers and other rural households. As a result, many authors have recommended methods and approaches for bridging this gap in the design and development of digital innovations to make them more aligned and accessible to the needs and preferences of marginalized groups of people such as through the use of local languages and other user-centric features (McCampbell et al. 2022; Molina-Maturano et al. 2022; Müller et al. 2022; Hernandez et al. 2024; Lahiri et al. 2024).

Based on the aspects pointed out above, we propose 'accessibility' to digital technologies and services for marginalized groups of people and regions as one of the key dimensions of digital inclusivity. We also propose four indicators within this dimension as summarized in Table 1 below.

Usability of digital innovations

Access to digital tools and services does not therefore necessarily translate to their adoption and use. People with low levels of formal education and skills, limited exposure, and experience with digital innovations, or with disabilities such as poor eyesight or hearing are likely to face barriers in using digital innovations (Porciello et al. 2022; McGrath et al. 2023). Inclusivity can therefore be enhanced by enabling marginalized groups to use these innovations, such as through training and other forms of support (Qureshi 2023). These skills include general literacy, digital skills, and strategic skills that support marginalized groups to use and manage digital innovations (Van Dijk and Hacker 2003; Tewathia et al. 2020; Fahmi and Savira 2023; Fauzi et al. 2021). Hernandez et al. (2024) also recommend complimenting digital innovations with non-digital options to make them more usable. In addition, digital innovations should be desirable to marginalized groups (Kudama et al. 2021; Kieti et al. 2022). For instance, Engås et al. (2023) argue that in developing and deploying digital tools and services, the intended users should be offered an opportunity to interact with the tools or services before committing to using them to assess their desirability and value.

During use, some digital innovations can arouse anxiety and stress to marginalized groups either because they are too complex or demand a radical change in their daily routines and practices (Stone 2022; McGrath et al. 2023). Comfort in using digital innovations, which can be attained through aligning the innovations to the social and cultural context of intended users, can be important in enhancing their acceptability and use (van der Burg et al. 2019; Steinke et al. 2021; Kieti et al. 2022). In addition, marginalized groups seldom use digital innovations in isolation and usually rely on social networks such as immediate family, neighbours, or fellow members of community-based associations to make decisions on whether a digital innovation is worth using, and how to use it (Stone 2022). These social networks can be instrumental in bridging skill gaps and mitigating anxiety among users, as demonstrated by Manalo IV (2013), who found that Filipino youth were instrumental in fostering the use digital agricultural services by their elderly parents. Trust, goodwill, and nature of interaction between organisations that promote digital innovations and marginalized groups also determine the extent to which the latter find the innovations to be desirable and valuable (Jenny C Aker et al. 2016a; Agyekumhene et al. 2020; Kieti et al. 2022). In Bangladesh for instance, 'info-ladies' who form part of the government extension system have been instrumental as trustworthy agents that support women smallholder farmers to access and use digital tools and services (Hernandez et al. 2024).

Given these aspects, Table 2 below outlines the four indicators of digital inclusivity that we propose under the dimension that we label as 'usability.'

Table 1 Indicators of accessibility

Description of the dimension	Indicators of digital inclusivity	Key sources of literature
Digital infrastructure and digital innovation packages are intentionally made known, available, and affordable to marginalized groups of people	i. The digital innovation package is aligned with the digital **infrastructure** in areas where marginalized groups of people live. ii. Digital innovation packages are intentionally made **affordable** to marginalized groups of people. iii. Marginalized groups of people are **adequately informed** of the digital innovation and its benefits. iv. Information on technology use habits, preferences, desires, and competencies of marginalized groups of people is analyzed and actively influences the **design** of the digital innovation.	Hernandez et al. (2024) Lythreatis (2022) Deichmann et al. (2016) Müller et al. (2022), Molina et al (2022), and Tsan et al. (2019)

Table 2 Indicators of usability

Description of the dimension	Indicators of inclusivity	Key sources of literature
Marginalized groups have skills, opportunities, and desire to continuously use the promoted digital innovations	i. Marginalized groups find the digital innovation to be **desirable and comfortable** to use. ii. Marginalized groups have the required **skill sets** to make use of the digital innovation iii. The social, cultural, and financial implications of using the digital innovation are **transparent** to marginalized groups. iv. There are sufficient **social networks** to support the assessment and use of the digital innovation by marginalized groups	Dey and Ali (2016), Kieti et al. (2022), Qureshi (2023) Fahmi and Savira (2023) Jenny C Aker et al. (2016a), and Manalo (2013) Tewathia (2020)

Benefits of the digital innovation

Efforts are being made by various organisations to 'digitize' marginalized groups of people and regions within FWL systems. Do these marginalized groups embrace the promoted digital innovations? This question, posed by Hashim et al. (2012) calls for an examination of the tangible benefits of digital innovations to the day-to-day lived of the people who are often considered marginalized, and targeted with digital innovations. The rate of use of digital innovations, especially among marginalized groups in less industrialised countries, remain low, partially due to lack of tangible benefits (Deichmann et al. 2016; Maru et al. 2018; Adenle et al. 2019; Abdulai 2022a). In addition, adoption and use of digital innovations are misleading indicators of inclusion if used in isolation, since there might be negative impacts of adoption and use, thus leading to exclusion (Hennessy et al. 2016). The term 'digital dividends' has been coined to refer to the value that digital innovations provide to marginalized groups of people and society in general (World Bank 2016). There is a need to unpack what this value means and how it can be attained.

A key concern over just and socially inclusive digital innovation is whether the problem being addressed is relevant to marginalized groups of people (Jiménez and Zheng Jimenezand Zheng; McCampbell et al. 2022). Digital innovations demand a change, not just in technological aspects, but also in the pre-existing social and cultural norms. Such changes should be valuable and relevant to marginalized groups in realizing their day-to-day goals and aspirations (Jiménez and Zheng 2018; Hidalgo et al. 2024). Besides being relevant, digital solutions are only beneficial if they are reliable and can be delivered in a timely manner (Jenny C Aker et al. 2016a; Tsan Michael et al. 2019). For example, digital early warning systems for drought and floods are only beneficial is such services and tools are reliable and are communicated in time to help mitigate climate hazards (Dey and Ali 2016; van Ginkel and Biradar 2021). Carter (2022) also point out that the efficacy of digital innovations in providing a solutions needs to be verifiable to marginalized groups as well as other actors in FWL systems. This process takes time and resources, which should be made available in a just and socially inclusive process (Van Dijk and Hacker 2003; Dey and Ali 2016).

The benefits of digital solutions depend on how well the solutions can be sustained in the long run. For example, successful ICT for development initiatives requires robust financial, legislative, and social frameworks for long-term viability, which often lack in time-bound development projects (Dey and Ali 2016; Utami et al. 2021). Besides this temporal aspect, spatial scales also determine how beneficial a digital solution are to marginalized groups of people. While some digital innovations directly benefit marginalized groups within FWL systems such as smallholder farming households, other benefits are accrued at communal or national scales, thus indirectly benefiting marginalized groups (Jiménez and Zheng 2018; Touri 2024). For instance, digital tools and platforms have been found to facilitate transparency and democratic participation in managing river basins and agricultural development programs (Munthali et al. 2018; Panganiban 2019; Chiles et al. 2021; Utami et al. 2021). Digital tools have also been applied as decision support tools to guide communal benefits such as equitable distribution and use of water, or to monitor and mitigate the degradation of forests due to agricultural expansion (Wallace and Gregory 2002; Nhamo et al. 2022; Kotir et al. 2024). While such tools are meant to be used by organisations such as government agencies that represent the interests of marginalized groups, the actual benefit to the latter needs to be assessed.

In Table 3, we outline five indicators of digital inclusivity elicited from literature under the dimension that we label as 'benefits'.

Participation in the digital innovation process

As digital innovations are promoted and used within FWL systems, concerns are being raised over the role of marginalized groups in contributing to the development, use, and governance of these innovations (van Bruggen et al. 2019; Hoolohan et al. 2021; Nyadzi et al. 2022; Peddi et al. 2023). Some authors have pointed out that marginalized groups are experts in indigenous and local forms of knowledge such as traditional methods of weather forecasting (Nyadzi et al. 2020; Peddi et al. 2023). These marginalized groups are sometimes consulted for their knowledge and expertise when digital innovations are being developed, thus advertently or inadvertently contributing to digital innovation (Radjawali et al. 2017; Maru et al. 2018; Rotz et al. 2019).

Table 3 Indicators of Benefits

Description of the dimension	Indicators of inclusivity	Key sources of literature
The digital innovation provides a solution that is relevant and reliable to marginalized groups	i. The solution offered by the digital innovation is **relevant and valuable** to marginalized groups ii. The digital innovation provides a solution in a **timely and reliable** manner. iii. The **efficacy** of digital innovation in providing a solution can be verified. iv. There are financial, social, or legislative arrangements to **sustain** the benefits of digital innovation in the long run. v.The digital innovation provides a **social value** for marginalized groups of people at community and landscape levels.	Aissaoui (2022), Daum et al. (2022), Panganiban (2019), Khoza et al (2021), and Munthali et al. (2018) Jimenez and Zheng (2018) World Bank (2016)

Table 4 Indicators of participation

Description of the dimension	Indicators of inclusivity	Key sources of literature
Marginalized groups have power and agency to meaningfully participate in the digital innovation process	i. Marginalized groups have **power and agency** to contribute to the digital innovation ii. The **intellectual property** of marginalized groups in the digital innovation is acknowledged and adequately compensated. iii. The digital innovation does not disrupt **alternative forms of innovation** that are valuable to marginalized groups. iv. Marginalized groups can adequately participate in defining and developing **rules and discourses** that govern the digital innovation	Peddi et al. (2023) van Bruggen et al. (2019) Engas (2023) Radjawali (2017) Nyadzi et al. (2022) Agyekumhene et al. (2020) Porciello et al. (2022)

This knowledge and expertise can be harnessed through approaches such as citizen science, participatory mapping, and participatory modeling (Radjawali et al. 2017; van Bruggen et al. 2019; Nyadzi et al. 2022; Hidalgo et al. 2024). From a responsible and socially inclusive innovation standpoint, such processes should not be extractive, and the intellectual property and contributions made by marginalized groups should not only be fostered, but also assessed, acknowledged, and adequately compensated (Munthali et al. 2018; Agyekumhene et al. 2020; Hidalgo et al. 2024).

When co-creation with marginalized groups of people is sought, the quality and nature of their relationship with other actors within FWL systems is key (Wilmsen 2019; Latulippe and Klenk 2020). There are often unequal power relationships within FWL systems and the nature of relationships between various stakeholders and marginalized groups determine the extent to which the latter have power and agency to make adequate contributions to the digital innovation process (Wilmsen 2019; Peddi et al. 2023). In the process of co-innovation, it is ethical and responsible to eliminate these power asymmetries that often treat 'scientific' or 'technical' forms of knowledge as superior (van Bruggen et al. 2019; Latulippe and Klenk 2020). Moreover, there are sometimes radical and irreconcilable differences between digital innovations and 'indigenous' forms of knowledge and innovation (Klenk and Meehan 2015). In such instances, it is ethical for the two forms of knowledge to co-exist, rather than integrate (Klenk and Meehan 2015; Latulippe and Klenk 2020). A key aspect of participation is therefore aligning digital innovations to pre-existing socio-cultural contexts and preservation of alternative or local innovation processes that are valuable to marginalized groups (Ingram and Maye 2020; Latulippe and Klenk 2020). For instance, introduction of digital climate forecasting methods may disrupt and lead to the loss of traditional weather foresting methods such as the observation of bird migration patterns and knowledge on plant species (Nyadzi et al. 2022; Abdulai 2022b). On the other hand, the responsible use of digital innovations can be instrumental in preserving and archiving indigenous forms of knowledge and innovation, thus promoting inclusion (Peddi et al. 2023).

Participation of marginalized groups is not limited to innovation process itself, but also in the discourses, norms, and rules that govern the development and use of digital innovations. Actors such as government agencies and multinational enterprises often have influence in framing and setting agendas over the trajectories of digital innovations (Williams and Woodson 2019; Ludwig and Macnaghten 2020; McCampbell et al. 2021). As part of an inclusive and responsible process, marginalized groups should equally participate in these governance processes since they will be impacted, either directly or indirectly by such innovations (Béné et al. 2019). Digital tools can also be instrumental in facilitating democratic participation of marginalized groups in innovation processes (Panganiban 2019; Utami et al. 2021). For instance, Hoolohan et al. (2021) argue that open-source digital platforms can create avenues for democratic participation in water governance. As a result of the aspects pointed out above, we propose the four indicators of digital inclusivity outlined in Table 4 under the dimension that we label as 'participation'.

Mitigating potential risks and harm of digital innovations

Within FWL systems, there are often pre-existing inequalities due to social, cultural, and economic norms (Fitton et al. 2019). As a result, digital innovations might replicate or amplify these inequalities (Garcia 2011; Hankivsky et al. 2014; Abdullah 2015; Gurung 2018; Engås et al. 2023;

Tauzie et al. 2024). For example, when digital tools are applied for decision support within organisations such forest management authorities, they could mirror and multiply pre-existing gender inequalities within such organisations if decision making organs are dominated by men (Duguma et al. 2022; Elias et al. 2023). In addition, many digital innovations rely on large volumes of data collected from various sources, including from marginalized groups and the regions where they live. Data from external sources may also be introduced to marginalized groups as part of digital innovation processes (Maru et al. 2018; van der Burg et al. 2019). These datasets, as well as the processes used in their collection, processing, and use, may be abused in several ways. For instance, it may be used for surveillance and profiling of marginalized groups or commercialized without their consent (Gurung 2018; Maru et al. 2018; van der Burg et al. 2019). Establishing clear guidelines for ethical and responsible collection, processing, and use of data is therefore imperative from an inclusivity perspective (Taylor 2017; Fraser 2019).

Digital innovations could also cause undesirable changes to broader social and biophysical systems within the landscapes and communities of marginalized groups. For example, big data can influence decisions over how water resources are used for agriculture. If left unchecked, however, such decisions could lead to degradation of water resources when implemented in largescale and over prolonged periods of time (Hoolohan et al. 2021). Pre-existing socio-cultural norms, practices, and relationships within marginalized groups could also be eroded by digital innovations (Klerkx et al. 2019; Nyadzi et al. 2022). For instance change from manual to automated processes may result in loss of contact and proximity with soils, animals, and water, leading to changes in meanings attached to issues such as animal welfare or soil health (Carter 2022; Stone 2022; Abdulai 2022b; Engås et al. 2023). Some authors have also recommended having an explicit agenda for social inclusivity within digital innovation processes as a way of being intentional with inclusivity and reflective on their ethical and responsible innovation practices (Mutsvairo and Ragnedda 2019; Utami et al. 2021; Ndulu et al. 2023). If developed in partnership with marginalized groups, such a vision and guideline can be instrumental in mitigating potential harm, monitoring progress, and adapting to unforeseen negative impacts of the digital innovation (van der Burg et al. 2019; Prause et al. 2021; Iazzolino and Stremlau 2024; Touri 2024).

Based on the aspects elicited above, we propose the four indicators of digital inclusivity in Table 5 under the dimension that we label 'risk mitigation'.

Table 5 Indicators of risk mitigation

Description of the dimension	Indicators of inclusivity	Key sources of literature
Potential risks of the digital innovation to marginalized groups are identified and mitigated	i. The risk of the digital innovation enforcing **pre-existing inequalities** among marginalized groups is identified and mitigated. ii. Measures are put in place to protect marginalized groups against **data misappropriation.** iii. Potential negative impacts of the digital innovation on **biophysical and social systems** is assessed and mitigated iv. There is an explicit **vision and agenda** for social inclusivity in the digital innovation process.	Fraser (2019) Gurung (2018) Abdulai (2022) Maru et al. (2018) Stone (2022) Taylor (2017) van der Burg et al. (2019) Iazzolino and Stremlau (2024)

A multi-dimensional framework for digital inclusivity

The five dimensions of digital inclusivity proposed in this study are interlinked in several ways. First, digital inclusivity attained within one dimension might lead to exclusion in another. For example, many organisations, including state agencies, are experimenting with approaches to make digital infrastructure affordable and available in the rural regions of less industrialised countries (Rotz et al. 2019; Abdulai 2022b; Hernandez et al. 2024). This will enhance inclusivity under the accessibility dimension. However, this inclusion might pose risks such as degradation of pre-existing cultural values and knowledge systems (Engås et al. 2023) thus leading to exclusion in the dimension of risk mitigation if such risks are not adequately mitigated. Second, the dimensions are not mutually exclusive. For instance, participation of marginalized groups can be under any of the other dimensions. Marginalized groups can participate in a digital tool's development through user-centered design (accessibility dimension), in peer-to-peer support networks for using digital tools and services (dimension of usability), in identifying the problems that are critical and relevant for digital innovations to address (benefits dimension), or in developing guidelines for ethical and responsible use of data (dimension of risk mitigation). Third, we find that the five dimensions can be applied to assess and promote digital inclusivity at any point in time across an innovation's trajectory, from inception and design to large scale application.

Across the dimensions and indicators of digital inclusivity, we also find that the social inclusion or exclusion of marginalized groups of people occur at different spatial scales within FWL systems. At a micro level, tools, and services such as digital climate forecasts or agricultural advisory services are for instance developed to be used by individual households or farmers and delivered through channels such as SMS, phone calls, interactive voice response, and smart phone applications. Digital inclusivity at this level is

focused on the opportunities, risks, and fairness of digital innovations for individuals such as rural households and family farms (Abdulai et al. 2022; Daum et al. 2022). At a meso level, focus is on inclusivity at a communal level such as villages or water use associations. Under the dimension of benefits for example, digital tools such as remote sensing or early warning systems might be intended for use in decision support by local governments rather than individual households (Wallace and Gregory 2002; van Ginkel and Biradar 2021; Kotir et al. 2024). In such instances, benefits are accrued for communities rather than at household level. At a macro level, digital inclusivity could be assessed and attained based on its impact on the broader biophysical or socio-cultural landscape such as changes in pre-existing socio-cultural norms or ecological systems caused by the digital innovation (Hoolohan et al. 2021; Carter 2022; Stone 2022).

As a result of these interlinkages, we propose a multi-dimensional framework of digital inclusivity for a holistic and nuanced assessment and fostering of digital inclusivity. This framework is presented in Fig. 1. In the next section, we will discuss the theoretical and practical value of this multi-dimensional framework.

Discussion

We have developed a five-dimensional framework with twenty-one indicators of digital inclusivity across the dimensions from our review and synthesis of the literature. There are two important implications that emerge from these findings. First, we discuss the implications of our framework for theoretical debates on inclusive and responsible digital innovation processes. Second, we reflect on the practical implications of such a framework, including the proposed indicators, as a metric for assessing and fostering digital inclusivity strategies by organisations such as state agencies, knowledge institutions, civil society organisations, private enterprises, and community-based organisations.

A multi-dimensional and intersectional approach to digital inclusivity

We started by pointing out the need for standard guidelines and metrics for fostering digital inclusivity in FWL systems, especially in the context of less-industrialized countries (Tsan Michael et al. 2019; Lioutas et al. 2021). The responsible research and innovation (RRI) framework,

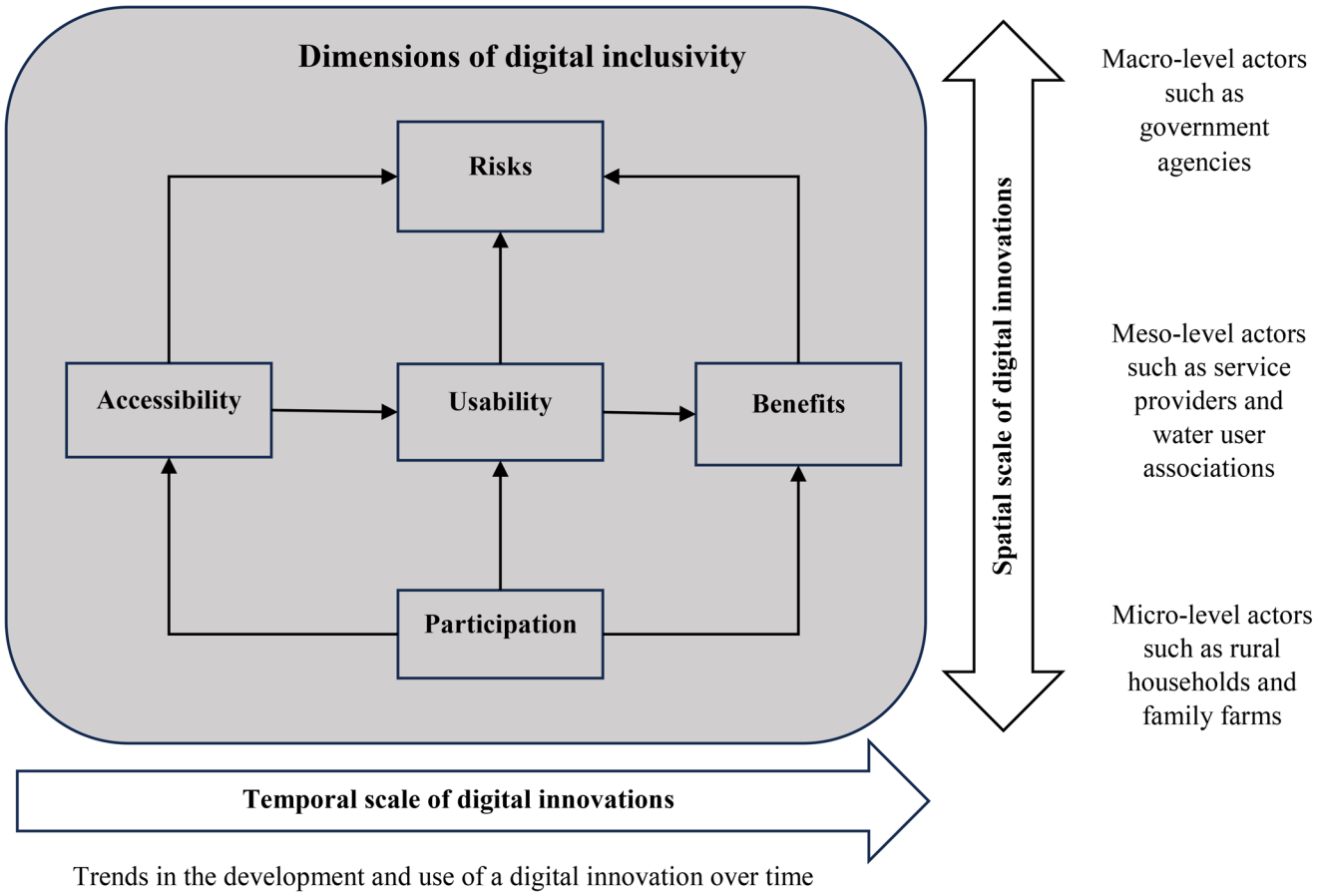

Fig. 1 A multi-dimensional framework for digital inclusivity in FWL systems

with its dimensions of anticipation, inclusion, reflexivity, and responsiveness is promising as such a framework (Fraser 2022). Our analysis has revealed key additions and modifications that can be made to the RRI and other current frameworks to develop metrics for just, responsible, and socially inclusive digital innovation processes in the FWL systems of less industrialized countries. Digital innovations are increasingly being promoted in the rural regions of less industrialised countries, where many people have little formal education, have minimal wealth, and live in socio-cultural contexts that are incompatible with technocentric development paradigms (Abdulai 2022a; Iazzolino and Stremlau 2024). Our explicit focus on the inclusion and fairness of these marginalized groups of people is therefore necessary in such a context. Such a focus lacks in current debates on responsible and just innovation. For instance, while the RRI frame has inclusion as one of its dimensions, this is conceptualized as the inclusion of different stakeholders such as through open innovation processes (Stilgoe et al. 2013; Fraser 2022), rather than the inclusion of marginalized groups of people within innovation systems.

In digital inclusivity literature, as well as broader inclusive innovation literature, participation of marginalized groups of people in innovation processes has been cited as a key elements of a just and socially inclusive innovation process (van Bruggen et al. 2019; Latulippe and Klenk 2020; Steinke et al. 2021). One of the critics of participatory approaches is that it ignores the power relationships between stakeholders and how that influences the extent to which marginalized groups of people have the agency and power to meaningfully engage and participate in innovation processes (Latulippe and Klenk 2020; Engås et al. 2023; Peddi et al. 2023). Additionally, participatory approaches are often criticized for considering participation as an end goal, and ignoring other forms of justice, particularly distributive justice and epistemic justice, in the pursuit of just and socially inclusive processes (Collins and Ison 2009; Moragues-Faus 2017; Boogaard 2021; Shostak 2022).

While participation is still a key aspect of inclusivity and can be a desirable end goal for marginalized groups (Opola et al. 2023), we propose that participation needs to be explicitly defined in digital inclusivity processes, by including tangible indicators on how marginalized groups can actively participate in a just and ethical manner. Our proposed indicators range from participation of marginalized groups in the development and use of a digital innovation, to more broader indicators such as participation of marginalized discourses and logics of innovation. For example, digital innovations might disrupt alternative paradigms of innovation such as agro-ecological transitions (Carter 2022). Digital innovations that are participatory, and therefore inclusive co-exist with alternative paradigms of innovation that are valuable to marginalized groups. Our findings also show that when participation is considered in isolation, other forms of social exclusion such as reinforcement of pre-existing inequalities might occur thus demonstrating a need for a multi-dimensional approach to digital inclusivity.

Indicators under the topic of 'risk mitigation' bring a more nuanced perspective that assesses an additional dimension of inclusivity: potential harm through the application of digital innovations for development-related solutions. Beyond what is commonly referred to as the 'digital divides' (Gurung 2018; Vassilakopoulou and Hustad 2021; Lythreatis et al. 2022) or the focus participation, our framework addresses potential harm that digital tools and services can either advertently or inadvertently cause (Heeks 2022; Mann 2018; Stone 2022). These risks are likely to be more severe in the context of vulnerable communities that do not have sufficient safety nets and suffer more from exclusion (Adenle et al. 2019; Rotz et al. 2019). This perspective of ethical responsibility is taken up by the responsible innovation approach and its stress on anticipation of consequences and responsiveness to peoples' values. While our framework shares this ethical concern with the AIRR framework, our focus is on the inclusivity of marginalized groups of people, particularly on the FWL systems of less industrialised countries. We also focus on indicators of risk mitigation in the context of digital innovations. These two key issues are not currently addressed in responsible research and innovation literature.

In general, we move beyond technocentric approaches focused adoption and diffusion of innovations to marginalized groups of people and employ a more critical and multi-dimensional approach to digital inclusivity. We also move beyond the operational vagueness of current frameworks by offering concrete and measurable indicators of digital inclusivity. By this, an operational and ethically informed framework is created that is suitable to promote digital inclusion in FWL systems. While we acknowledge that marginalized groups of people are not homogeneous, and that there are specific needs and interests of sub-groups such as women, or elderly farmers (Abdulai et al. 2022; Mahlangu et al. 2022), we adopt an intersectional approach that collectively address the needs of people likely to be marginalised due to resource constraints, education status, age, gender, or physical disability. However, the overarching aspect that leads to exclusion and vulnerability across these marginalised groups is low wealth status. Table 6 below presents the five dimensions and 21 associated indicators of digital inclusivity elicited from this study. These can form the basis for a digital inclusivity index, a guide for fostering and assesing the responsible and socially inclusive development and application of digital innovations in FWL systems.

Table 6 Dimensions and indicators for digital inclusivity in FWL systems

Dimension	Indicators of inclusivity
Risk mitigation *Potential risks of the digital innovation to marginalized groups are identified and mitigated*	RI. Have pre-existing inequalities among marginalized groups been identified and actions taken to mitigate the risk of re-enforcing these inequalities? R2. Have measures been put in place to guard marginalized groups, and society in general, against data misappropriation? R3. Has there be an assessment of the digital innovation's potential negative impact on socio-cultural and bio-physical landscapes and mitigation strategies put in place? R4. Is there an explicit vision and agenda for social inclusivity within the digital innovation process?
Accessibility *Digital infrastructure and digital innovation packages are intentionally made known, available, and affordable to marginalized groups of people*	A1. Is the digital innovation package aligned to the available digital infrastructure in areas where marginalized people live? A2. Are digital innovation packages, including digital infrastructure, intentionally made affordable to marginalized groups? A3. Have appropriate and adequate efforts been made to make marginalized groups aware of the digital innovation and its benefits? A4. Are the technology use habits, preferences, desires, and competencies of marginalized groups analyzed and integrated into the digital innovation's design and development process?
Usability *Marginalized groups have skills, opportunities, and desire to continuously use the promoted digital innovations*	U1. Is the digital innovation desirable and comfortable to use for marginalized groups? U2. Do marginalized groups have the required skill sets to use and derive benefits from the digital innovation? U3. Are the financial, social, and cultural implications of using the digital innovation transparent to marginalized groups? U4. Are there sufficient and suitable social support networks to facilitate the use of the digital innovation by marginalized groups?
Benefits *The digital innovation provides a solution that is relevant and reliable to marginalized groups*	B1. Does digital innovation provide a solution to a problem that is relevant and valuable to marginalized groups? B2. Is the solution provided by the digital innovation timely and reliable? B3. Can the efficacy of the digital innovation in providing the solution be verified? B4. Are there financial, social, and legislative arrangements in place to ensure that the solution offered by the digital innovation can be sustained? B5. Does the digital innovation create a social value to the communities of marginalized groups?
Participation *Marginalized groups have power and agency to meaningfully participate in the digital innovation process*	P1. Do marginalized groups have the power and agency to meaningfully and actively contribute to the digital innovation process? P2. Is the intellectual property of marginalized groups assessed, acknowledged, and adequately compensated? P3. Can the digital innovation co-exist with alternative forms of knowledge and innovations that are valuable to marginalized groups? P4. Do marginalized groups meaningfully participate in defining the rules, policies, and discourses that govern and guide the digital innovation?

Towards a digital inclusivity index in food, water, and land systems

As indicated earlier in this review, one of the drawbacks to developing and accelerating a digital inclusivity strategy by actors such as state agencies, development organisations, local authorities, and civil society organisations is the lack of clear and concise indicators or guidelines for the process (Adenle et al. 2019; Tsan Michael et al. 2019). Within FWL systems, inclusivity indices such as the Women's Empowerment in Agriculture Index (WEAI) have been proposed and adapted to various contexts to foster social inclusivity in agricultural development interventions (Alkire et al. 2013; Malapit et al. 2019). In digital innovation, tools such as the Rapid Inclusivity Assessment Tool and the Australian Digital Inclusion Index have been proposed and used to foster and assess inclusivity in the design and use of digital innovations (Müller et al. 2022; Wilson et al., 2019). These indices provide metrics for assesing the inclusivity of digital innovation outcomes, such as tools and services to marginalised groups of people, and society in general.. Based on the multi-dimensional inclusivity framework presented in this study, we propose a holistic and multi-criteria digital inclusivity index that adresses various aspects of social inclusion, empasising not only inclusivity in the outcomes of digital innovations but also inclusivity within the innovation process, including the discourses and paradigms that guide it.

The digital inclusivity index can offer a comprehensive approach to understanding, assessing, and fostering digital inclusivity in FWL systems, presenting tangible actions and strategies towards realizing this goal. The multi-dimensional framework, as well as the proposed index can be useful for different actors to achieve various purposes in enabling responsible and socially inclusive digital innovation in FWL systems. For government agencies, it can be an instrument for enabling, assessing, and regulating the responsible and ethical application of digital innovation. For private actors such as technology firms, it can be a tool to evaluate and reflect on their own practices and develop strategies for responsible and inclusive digital innovation processes. For knowledge institutions, it can provide a theoretical basis

for examining digital innovation processes. For community-based and civil society organisations, the index can offer metrics for assessing the short- and long-term social impact of digital innovations to livelihoods, communities, and landscapes. For development agencies, it can provide the basis for assessing and identifying organisations that are involved in socially responsible and inclusive digital innovation processes. Across the different actors, the framework and index can provide a platform and tool for collaboration by creating a common language and understanding on the responsible and socially inclusive development and use of digital innovations in FWL systems. By providing tangible metrics for digital inclusivity, different actors can assess, enable, communicate, and reflect on their own processes and methods, thus facilitating the co-creation of knowledge and innovation processes on digital inclusivity. Such as collaborative paradigm on innovation has been proposed as an imperative for just and fair innovation processes, in comparison to linear 'expert' driven approaches (Wieczorek and Hekkert 2012; van der Merwe and Grobbelaar 2018; Cummings et al. 2021).

However, the implementation of this index can be expected to face several challenges. First, while we used an interpretive and critical approach to literature synthesis, most of the evidence used in this study is derived from 'formal' or 'scientific' forms of knowledge and knowing (Chat away et al. 2014; Telleria 2020; Peddi et al. 2023). To ensure a just and socially inclusive approach to the index development, it is therefore necessary to validate and co-develop the index with various actors, including marginalized groups of people within less industrialised countries. This will ensure that the indicators proposed in this study, as well as their process of development are relevant, culturally sensitive, participatory, and usable, in line with the principles proposed in this study. In addition, attention to hidden power structures is paramount in creating meaningful participatory spaces– real collaboration and dialogue on consequences might be hampered by status and gender hierarchies (e.g. McCampbell et al. 2022). Data availability to measure the indicators also needs to be carefully considered– disaggregated data on rural areas is usually rare and demands extra costs and time from implementers or organisations applying the proposed framework.

Conclusion and future directions

The transformative potential of digital innovation in addressing various challenges within the food, land, and water systems of less industrialized nations is evident. Nevertheless, the concern that segments of the population, particularly those with limited formal education and livelihood resources, and specifically those marginalized by prevailing sociocultural norms, might be excluded from the benefits of these innovations is substantial. Moreover, the potential risk of digital innovation causing harm to these groups cannot be overlooked. We have developed a compressive five-dimensional framework, with a set of twenty-one indicators for assessing and fostering a just and socially inclusive development and use of digital innovations in the FWL systems of less industrialised countries. This framework moves beyond the technocentric approach of focusing on diffusion and adoption of digital innovations by providing a critical and holistic assessment of digital inclusivity. The multi-dimensional framework, together with the proposed set of indicators, lays the groundwork for developing a digital inclusivity index, a tool for assessing and fostering digital inclusivity in FWL systems. Such an index needs to be developed in a collaborative and socially inclusive manner, in accordance with the digital inclusivity principles proposed in this study.

We propose two further studies to address the limitations of our study. First, research, particularly using transdisciplinary methods, could explore the validity and credibility of the multidimensional framework, as well as the digital inclusivity index to different geographical and sectoral contexts within food, land, and water systems. This study could also investigate whether there are any hierarchies between the five dimensions of digital inclusivity proposed in this study. Second, while we adopt an intersectional approach to digital inclusivity, further research could explore if the dimensions and indicators proposed within this study are generic for all typologies of marginalized groups of people within the FWL systems of less industrialized counties, as well as within industrialized countries.

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Declarations

Competing interests The authors declare that there are no competing interests.

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