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# Harnessing synergies across networks to drive sustainable food systems in India

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ABSTRACT

The concept of food systems is useful to account for activities and stakeholders, and their environmental and health impacts, across the food supply chain. Cross-sectoral coordination and site-specific implementation can help achieve synergistic outcomes for food, environment, and health. However, most policies and interventions are designed in silos, and may have unintended consequences that negate their intended objectives. This study aims to identify the policy actions and actors that can have the most synergistic desired outcomes for sustainable and healthy food systems. The study characterises the drivers, pressures, state, and impacts of change in selected food systems across diverse geographies of India, and recommends potential response actions. Secondary qualitative data from researchers, and document analysis of grey and policy literature is used to develop a theory of change for these food systems. A network of actions and actors is constructed to identify the most impactful actors and actions to achieve sustainable and healthy food system outcomes in India. Public education and awareness, farmer capacity development, and streamlining sustainable and healthy diets through social safety net programmes emerge as important pathways with high impact on environment, food, and health. The analysis also highlights the importance of local actors in implementing devolved governance of high-level policy and programme interventions.

## 1. Introduction

The global industrial agricultural system prioritises yield efficiency and an overall increase in global food production and stocks. However, improved productivity often does not translate to better nutrition or reduced environmental impact [1]. Government planning and policy, especially in lower and middle income countries (LMICS), are usually geared toward ensuring food sufficiency, through market and infrastructure development to promote production and distribution of food [2]. However, households often struggle to achieve dietary diversity and nutritional sufficiency, with larger-level socio-economic and structural factors posing barriers to healthy diets. For example, urbanising lifestyles, liberalised markets, and industrial production can render people incapable of procuring or affording fresh and nutritious foods [3,4]. At landscape level, intensive agro-industry to meet sufficiency and profit goals can result in land degradation [5], loss of biodiversity [6], and pollution, whilst also eroding human health and wellbeing [7]. Globally, while large-scale food trade has reduced hunger in some cases, overall, it has created cross-scale geographic dependencies that also reduce local self-sufficiency [8], and climate change resilience among both exporters and importers [9].

Decentralised, locally adapted systems are needed to improve access to sustainable, nutritious, and just food [10,11]. The concept of food systems helps to contextualise scale and impacts of food and agricultural policy on social-ecological systems. A food system includes all the activities and actors involved in the production, processing, distribution,

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and consumption of food [12]. It thus encompasses the many social-ecological implications of food, from environmental and population health, to governance and access. A food systems approach can identify leverage points in policy and implementation to improve outcomes at different scales. Leverage points are defined as loci and processes within systems where interventions can be directed to achieve widespread change (e.g Ref. [13]). This paper identifies the gaps, bridges, and leverage points between food systems and the environment and human health, from a governance and policy perspective. Previous research has established links between global environmental change and public health at a global scale [9], and food systems and environmental sustainability in India [14]. However, a comprehensive systems view of the links between environment, food, and health is lacking not only in India, but much of the world [15]. This research further develops these links, with an explicit environment-food-health nexus, within the specific multidimensional context of India.

In India, rice and wheat form a significant part of food grains produced [16], in addition to other grains like millets, sorghum, and maize [17]. A sizeable population benefits from the public distribution system (PDS) which provides subsidised staples to eligible households under a given income threshold [18]. Overall consumption of fruits and vegetables by the population remains below that prescribed by dietary guidelines, partly due to socioeconomic inequalities, and partly due to poor market penetration [19]. However, urban intake of fruits, vegetables, dairy, and meat is increasing, as market access, incomes, and lifestyles are changing [20]. With this lifestyle change also comes an increase in consumption of processed and ultra-processed foods, which if unchecked can cause malnourishment and chronic disease [21]. Studies estimate that in India, alleviating food and nutritional poverty can have only a small increase in environmental footprint, whereas reducing overconsumption and food wastage nationally can significantly reduce environmental footprint [22], although this may make sustainable diets more expensive [23]. This consideration is especially important in light of the fact that arable land and water are limited resources in the largely agrarian India [24]. Various government policies and programmes have been instituted to support farmers to maintain or increase farm productivity, for markets to maintain steady distribution and prices, and to enable households to maintain food and nutritional security and health [14]. However, because these initiatives can be siloed, they may often have suboptimal or even negative impacts on the environment (e.g. biodiversity, groundwater, soil depletion), and even on human health (e.g. dietary shifts to less nutritious foods).

In this paper, the questions are: i) What are some of the key changes and associated challenges across Indian food systems? ii) What are the most impactful actions in these food systems that could effect positive outcomes for both human health and environment? and iii) Who are the actors most capable of implementing these actions? The attempt is to answer these questions with a case study approach to characterise food systems changes and challenges, using the Drivers, Pressures, State, Impacts, and Responses (DPSIR) framework to identify the most impactful actions, and network analysis to identify the most capable actors. In doing so, the paper categorises actions and actors from the most generally applicable pathways to the more locally specific actions, and highlights the gaps, bridges, and feedback loops in the policy landscape related to food systems. Previous studies examining Indian food systems have looked at specific components of food production (e.g. Ref. [25]), distribution (e.g. Refs. [26,27]), consumption (e.g. Ref. [23]), or governance (e.g. Ref. [14]), but without a wider perspective on how these interface, and what specific actions can be taken by stakeholders across various scales. The results and recommendations from this study can suggest to policymakers and practitioners effective ways through which they can achieve multiple objectives of food and nutritional security, environmental sustainability, and human and environmental health.

## 2. Methods

### 2.1. Characterising Indian food systems through structured researcher workshops and DPSIR

The sample frame for this study was six study sites under the Sustainable and Healthy Food Systems (SHEFS) project, spread across the states of Gujarat, Karnataka, Maharashtra, and Sikkim. These six sites were considered to be representative case studies of diverse Indian food systems. Between 2018 and 2021, researchers collected various types of data at these sites, to investigate their sustainability and contribution to human health. The case studies sought to answer questions about environment, food, and health aspects of food systems specific to each site. A summary of the details of study area, methods, and findings at each site can be found in references cited in Table 1. The research questions, participant stakeholders, and data collection and analysis methods used at the sites varied; the contribution of these case studies to this research article is a broad sample of stakeholders involved directly or indirectly in food systems across diverse geographies. In 2020–21, findings from the six case studies were synthesised to derive policy implications for each site. This was done using a theory of change methodology describing the problem, potential solutions, status quo, required changes, and identifying stakeholders involved in driving the changes. Policy impact pathways workshops drawing on Young et al. [28] were conducted virtually for each study site. Each workshop was led by the first author and one policy facilitator (see Acknowledgements), who were consistent across all six virtual workshops. Each workshop involved two researchers who worked at the respective study site (co-authors), thus totalling four participants at any given workshop. The co-author cohort consists of three male and ten female researchers, with between two and thirty years of experience in social-ecological systems research. This study reports collective results from these six workshops, scaling policy recommendations from local to national level.

Each workshop consisted of four phases, namely i) problematising the key findings, contextualising them within the environment-food-health nexus, and identifying a general cause and solution ii) identifying status quo and desired changes in policies, investments, processes, and attitudes, iii) listing relevant actors and actions in a theory of change framework at national, state, and local level, and iv) placing actors along an alignment/influence matrix to identify synergies and prioritise actions. Workshops were usually conducted online and in two sessions, about an hour long each. Problematising and identifying changes was conducted in the first session, during which two researchers representing each study site, together with the first author and policy facilitator, described a comprehensive social-ecological landscape of their respective site (Table 1). The theory of change and alignment/influence matrix activities were conducted in the second session. Document analysis was conducted between the two sessions by all four workshop participants, to retrieve further information about relevant actors, policies, and pathways for each site.

The DPSIR framework is a comprehensive systems approach developed to speak to policymakers and practitioners [35]. It has been adapted and applied to various conceptual models and real-world case studies [36]. This approach helps identify causal relationships, feedback loops, and social-ecological interactions within systems [37]. The DPSIR framework can be used to summarise and assess system interactions both qualitatively and quantitatively [38]. This assessment in turn can aid in prioritising areas for improved and adaptive governance [39], and in developing multiple pathways to achieve desired systemic change by addressing drivers and pressures [40]. Thus, the DPSIR framework provides a view of not only the actors, processes, and interactions in a system, but also of leverage points to effect changes within the system. The paper mapped the synthesis from the six case studies onto this framework, with policy impact pathways as the response actions to address the current drivers and pressures (Fig. 1). Drivers, pressures, state, and impacts were identified in the first workshop during which

**Table 1**
Summary of the locations, investigations, and findings, and data collected from the six case studies.

| Food system | Research question | Environment aspect | Food aspect | Health aspect | Data collected | Axis of change | Reference |
|---|---|---|---|---|---|---|---|
| Banni grasslands (dairying) Gujarat | How does commercial dairy affect pastoral livelihoods? | Increased use and import of fodder, water | Lower dairy intake, higher processed food intake | Nutrition and lifestyle changes | Qualitative, interviews, focus groups | Commercialisation | [29] |
| Baramati district (agroindustry) Maharashtra | How does agroindustry affect household nutrition? | Access to farms reduced along rural-urban gradient | Access to fresh, nutritious foods reduced among women | Women, children, and family health effects | Mixed, interviews, focus groups | Urbanisation | [30] |
| Baramati poultry (poultry) Maharashtra | How does commercial poultry affect food and environmental safety? | Increased drug and microbial load in waste, downstream environment | Reduced quality and safety of poultry products due to drugs | Antimicrobial resistance among producers, consumers | Soil, water microbial samples | Commercialisation | [31] |
| Bengaluru district (urban) Karnataka | How can urban systems support food pollinators? | Green spaces, urban food production can be improved | Consumption relies on pollinators | Pollinator-friendly urban spaces have co-benefits | Mixed, surveys, literature review | Urbanisation | [32] |
| BRT wildlife sanctuary (beekeeping) Karnataka | How do social-ecological trends affect pollinators? | Invasives, policies, hinder effective management | Unsustainable extraction exacerbates scarcity | Pollinator-friendly forest policies have co-benefits | Mixed, ecological surveys, interviews | Social-ecological | [33] |
| Dzongu district (agroecology) Sikkim | How do policy and trends affect local agroecology? | Conversion of local biodiverse farms to monocultures | Lower access and intake of fresh, nutritious foods | Nutrition and lifestyle changes | Mixed, interviews, focus groups | Social-ecological | [34] |

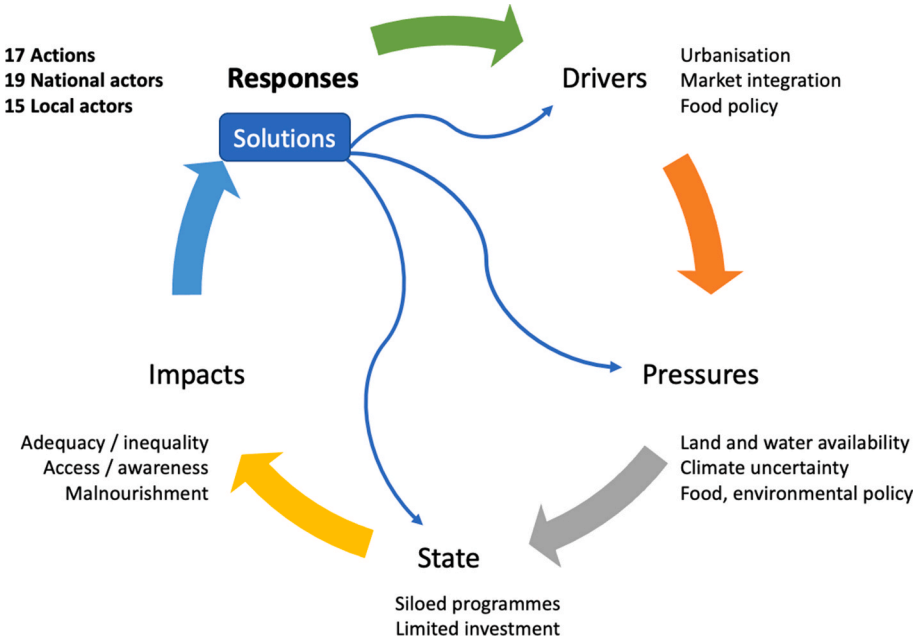


**Fig. 1.** Findings from the policy impact pathways workshops and DPSIR mapping exercise.

problem causes, solutions, and status quo were discussed.

### 2.2. Response mapping, synthesis, and impact scoring

Responses were derived from the theory of change and alignment/influence matrix exercises during the second workshop by all four participants at each of the six workshops. After all six workshops were complete, the first author combined the list of actions and classified and scored them. Actions were placed along the local to national, and general to specific scales, and were scored on their relevance to the environment-food-health nexus, and their level of engagement with institutional, capital, process, and attitudinal change, as outlined in the preceding phase. Outcomes related to food safety and nutrition were scored as health impacts, those related to food availability and access were scored as food impacts, and outcomes related to ecological and biophysical factors were scored as environment impacts. Scores were limited to zero for no link or change, and one for a link or change, and only direct impacts were scored. Impacts are presented as nexus scores for actions (Table 2), with higher nexus scores implying greater synergies across the environment-food-health nexus for the implementation of the action. Nexus scores were used to triangulate action ranks after considering degree centrality and hub scores (see below).

### 2.3. Network analysis to rank actors

Network analysis is a methodology based in graph theory, used to visualise and quantify relationships between entities such as actors, groups, actions, and impacts [41]. It is widely used across various fields such as analytics, biology, economics, sociology, and development planning to identify important nodes and flows of information, decisions, and resources. This paper used network analysis to identify the most interconnected and impactful actors who could implement the response actions emerging from the preceding phases. The first author conducted the network analysis and presented it to all co-authors for

**Table 2**
Recommended response actions, their degree centrality and hub scores in the network, and their impacts (1 = yes, 0 = no) on the environment-food-health nexus.

| Actions | Network scores | | Nexus scores | | | |
|---|---|---|---|---|---|---|
| | Degree centrality | Hub score | Enviro-nment | Food | Health | Total |
| Social engagement | 13 | 0.67 | 0 | 1 | 1 | 2 |
| Farming practices | 10 | 1 | 1 | 1 | 1 | 3 |
| Safety audit | 9 | 1 | 1 | 1 | 1 | 3 |
| Home gardens | 7 | 1 | 1 | 1 | 1 | 3 |
| Midday meals | 6 | 0.67 | 0 | 1 | 1 | 2 |
| Market linkages | 6 | 0.67 | 1 | 1 | 0 | 2 |
| Sustainable use | 6 | 0.67 | 1 | 1 | 0 | 2 |
| Influence demand | 5 | 1 | 1 | 1 | 1 | 3 |
| Poshan Vatika[a] | 5 | 1 | 1 | 1 | 1 | 3 |
| School gardens | 5 | 1 | 1 | 1 | 1 | 3 |
| Urban agrifood | 5 | 1 | 1 | 1 | 1 | 3 |
| Invasive alien control | 5 | 0.66 | 1 | 0 | 1 | 2 |
| Public gardens | 4 | 0.33 | 1 | 0 | 0 | 1 |
| PDS diversification[b] | 3 | 0.67 | 0 | 1 | 1 | 2 |
| Biodiversity conservation | 3 | 0.33 | 1 | 0 | 0 | 1 |
| UGI development[c] | 3 | 0.33 | 1 | 0 | 0 | 1 |
| Health monitoring | 2 | 0.33 | 0 | 0 | 1 | 1 |

[a] Poshan Vatika (nutrition garden) – community-owned local food gardens.
[b] PDS (public distribution system) – government subsidised food supply.
[c] UGI (urban green infrastructure) development – agrifood private and public enterprise.

consensus.

Information collected during the policy workshops was tabulated to document various possible actions undertaken by private entities (Citizens, Enterprises, NGOs), and governing institutions at district, state, and national levels (Table a). Where these institutions were nested, they were assigned a single action, which was considered executed through this operational hierarchy. State-level actors were listed where their specificity could not be bypassed between national-level actors and local actors and actions. Each actor was independently linked to an action, and a change score (generating institutional, capital, process, and attitudinal change). Actions were considered independent of one another, and networks were directed but not weighted, as in different case studies, the same actors and actions could have different impacts.

Each action, group of local actors, state-level department or board, and national-level ministry or institution, was defined as a vertex. The flow of hierarchy between these actors and actions was considered an edge. Networks and graphs were plotted in R [42] using the package 'igraph', and degree centrality and hub scores were calculated for each vertex. Degree centrality is the total number of edges connecting a given vertex with other vertices throughout the network, and hub scores accrue with vertices with more outgoing edges. By this measure, vertices with higher degree centrality are the actors and actions with greater throughput to generate impact. Higher hub scores identify the actors and actions that provide resource input to other actors to generate impact. Change scores were used to triangulate actor ranks after consideration to degree centrality and hub scores.

## 3. Results and discussion

### 3.1. Characterising change and challenges across Indian food systems

#### 3.1.1. Drivers of change

Across all six study sites, urbanisation and increased access to markets emerged as the main drivers of change in food systems. Food-related policies and programmes such as the PDS and agricultural subsidies were important drivers of change at four sites, and wildlife protection policies also influenced food systems change at two sites (Table 1, Table a). Urbanising lifestyles are leading to significant changes in food consumption in agropastoral systems [30]. This in turn affects diets, nutrition, and health of these populations on the one hand. It also affects the production practices in these areas, leading to more resource-intensive dairying for example, or more monoculture cash cropping [34]. Increased access to wider markets also promotes more intensive dairying, poultry, and farming to cater to these markets. This could lead to lesser domestic consumption of local and nutritious food, either as a choice, or due to lack of availability, both a result of production favouring market demand [29]. It may also lead to environmentally detrimental production practices such as unregulated use of antibiotics in poultry for example [31].

#### 3.1.2. Pressures

Existing food and environmental policies may exacerbate the changes driven by urbanisation and market access. Current food policy and programmes tend to have a productionist approach, incentivising cultivation of staple crops over local crops. The public distribution system and midday meal schemes may also form a negative feedback loop, inducing communities to consume low-cost staple foods over less accessible local and nutritious foods. At some sites, wildlife protection areas and policies related to them may inhibit traditional land management strategies [33,34]. Protectionist regimes may prevent practising of livelihoods such as pastoralism and beekeeping, which co-produce food and healthy landscapes by managing vegetation.

#### 3.1.3. State

The study found that a number of policies and programmes exist across the environment-food-health spectrum, and that modifications in the implementation of these would in most cases respond to the drivers, pressures, and impacts. Notwithstanding, it is acknowledged that arable land and clean water are constrained, and climate change introduces vulnerability to varying degrees within all the systems. Responses involving modification of existing policies and programmes are discussed in detail in the section that follows. It is also acknowledged that these response recommendations are formulated in an ideal state, and that their implementation could manifest in varied outcomes across space and time. Some of the responses (as indicated in Fig. 1), also termed actions (as listed in Table 2) have more synergistic outcomes for the environment, food production, and human health and wellbeing than others. Prioritising these responses or actions for modification of existing policy and implementation is likely to deliver greater benefits more efficiently.

#### 3.1.4. Impacts

The primary impacts emerging from the synthesis were reduced environmental access and production of fresh, safe, and nutritious foods, constrained access to and awareness of nutrition, and downstream environmental and health and wellbeing outcomes of these impacts. For example, lack of resource monitoring combined with climate change is leading to significant depletion of environmental food resources [33]. This study does not quantify these impacts, but uses them to guide the responses. For example, the responses outline how environmental enrichment can support biodiversity as well as human food and health needs [32].

#### 3.1.5. Responses: identifying impactful actions to respond to change

Up to 17 different responses were identified to address the drivers, pressures, and impacts (Table 2). Degree centrality scores indicated that social engagement to increase awareness about sustainable and healthy food was the action most connected to various actors in the network, and had direct impacts on food and nutrition, and health and wellbeing. Promoting and adapting farming practices to grow sustainable and healthy food was the second most connected action. It was also a prominent hub, and was linked to all three nexus nodes, implying that it is a high impact action. Conducting audits to ensure food and environmental safety was also a high impact action, with links to all three nexus nodes. Sustainable use of various forms of green spaces, improvement of social support services such as midday meals and PDS, and market linkages to incentivise sustainable and healthy food supply chains constituted the remainder of the important emerging responses.

### 3.2. The most impactful response actions and actors involved

#### 3.2.1. Social engagement to promote sustainable and healthy diets

Along the supply chain, this includes efforts by the Food Safety and Standards Authority of India (FSSAI), Non-Governmental Organisations (NGOs), and farmers to educate consumers about food safety norms and standards [43]. At household level, it includes efforts by the Ministry of Information and Broadcasting (MoIB), Self-Help Groups (SHGs) and Accredited Social Health Activists (ASHAs) to educate people about diet, nutrition, and health. In India, across the rural-urban gradient, access to fresh and nutritious food may be constrained by social mores such as caste and gender, or economic preference for cheaper subsidised staples. Thus, despite being relatively food sufficient, a significant portion of the Indian population suffers from nutritional insufficiency [44]. This nutritional insufficiency can be targeted at community level via public health centres and local schools, as well as public broadcasts and events organised by local Panchayats and Municipalities. Existing programmes in this vein include the Poshan Maah (Nutrition Month) and Poshan Jagruti Saptah (Nutrition Awareness Week) events organised by Gram Panchayats (village councils) [45]. In some cases, where cultural or cooperative structures around food already exist, state-level institutions like the Dairy Development Board and the Department of Tourism, and local businesses and cooperatives could play a role in engaging with the public on the nutritional value of fresh local foods, such as dairy and non-staple crops [46,47].

#### 3.2.2. Enabling sustainable and healthy food production through extension

Adoption of sustainable and healthy farming practices ranges from cessation of use of antibiotics in animal feed, and pesticides that endanger pollinators, to incorporating local plant and animal agro-biodiversity on farms to create circular economies using local manure and producing local food. The Indian Council for Agricultural Research (ICAR) and the Krishi Vigyan Kendra (Farm Science Centre, KVK) are national institutions that can train farmers in sustainable farming through their programmes. Examples of existing programmes include the National Mission for Sustainable Agriculture (agroecology), the Organic Mission (pollutant-free farming), and the Paramparagat Krishi Vikas Yojana (indigenous crop farmer development scheme) [48,49]. The Ministry of Agriculture and Farmer Welfare (MoAF&W), along with state Departments of Agriculture and Horticulture could also contribute to this. As concerns animal farming, the Ministry of Fisheries, Animal Husbandry, and Dairying (MoFAHD), as well as state-level departments under it, can train poultry and livestock farmers to identify illegal antibiotics in animal feed or other input products. Existing programmes include the National Livestock Mission (NLM under MoFAHD), and export market quality control protocols under the Export and Import Council of the Ministry of Commerce and Industry.

The government of India provides various extension services to farmers, including seeds, training, finance and so on, but a limited fraction of Indian smallholder farmers tend to access these services [25]. This is in large part because the services are fragmented across different departments and mandates [14]. Consolidating farmer support and extension services at one accessible nodal agency may make them more accessible and streamlined to farmers. The ICAR and KVK are national-level institutions that could work with Gram Panchayats and local Municipalities to ensure services are extended on the ground to farmers [26]. This includes education on chemical and antibiotic inputs, indigenous seeds and non-chemical inputs, training on farm design and management to optimise biodiversity and yield, and market linkages, including hybrid convergence solutions through public-private partnerships. Streamlining the process and offerings can help the government achieve impact on its ambitious schemes to double farmer income through sustainable intensification [50].

#### 3.2.3. Safety audits to leverage sustainable and healthy food supply chains

Guidelines for food production environments exist across multiple states, stipulating in particular the safe disposal of waste, to prevent environmental contamination. However, these guidelines are rarely enforced, and farmers may be unaware of them. It is contingent on local Municipalities and state Pollution Control Boards to ensure compliance with these guidelines, and regularly assess facilities for environmental safety. The Poultry Development Organisation along with the FSSAI and MoFAHD can facilitate third party audits for food safety, and also train farmers to test and report for food and environmental safety on a regular basis. The Drug Standards Control Organisation can also intervene by testing feed for resistance-inducing drugs. Across the spectrum of sustainable and healthy farming practices and safety audits, businesses and NGOs can play a role in educating farmers and consumers about safety and sustainability, supporting capacity development, and connecting farmers to consumers. Especially in urban areas, promoting awareness of food safety and food footprints is likely to influence consumer choice and market demand for safe and sustainable foods. For example, labelling and certification of antibiotic-free poultry can steer consumer awareness of food and environmental safety, which otherwise tend to be taken for granted. Food safety concerns have been known to have far-reaching and long-term effects in influencing consumer behaviour [51]. Existing urban supply chains such as online meat retailers provide a ready infrastructure to encourage food safety awareness and demand [52].

#### 3.2.4. The role of gardens in promoting sustainable and healthy diets

Promotion and enrichment of home gardens, Poshan Vatikas (nutrition gardens), public gardens, and school gardens are identified as separate actions because the motivation and execution of each of these actions is effected through different local and national actors, and their impact pathways vary by site. For example, school gardens can be used to change awareness and attitude about nutrition among children, but not necessarily contribute significantly to food production. Similarly, Poshan Vatikas are rural community gardens that can be used to propagate plant material and knowledge about traditional and pollinator-dependent foods [53]; these could also be introduced to cities. Among these, home gardens were most impactful because they leverage existing rural and urban schemes to enable citizens to grow food at home, and improve access to fresh, nutritious food. Public gardens were least impactful because they contributed more to pollinators than to food or nutrition. Planting and maintenance of Poshan Vatikas and public gardens could be executed via the National Rural Employment Guarantee Scheme (NREGS), generating employment for rural people, while simultaneously contributing to community nutrition and the environment. Community, school, and home gardens are likely to enhance dietary diversity of those who use them [54,55]. Alongside public health centres and schools, gardens are an important node to amplify awareness and education of sustainable and healthy diets at community level.

Urban green infrastructure is categorised as separate from these gardens, because it refers to multifunctional structures such as vertical or solar panel-sheltered greenspace, which also play a more ecological

role. Urban agrifood includes agricultural or aquaponic food production systems, which can be supported by local Municipalities and the Ministry of Urban Development infrastructurally, and State Departments of Agriculture and Horticulture technically. Depending on the form of urban green infrastructure or agrifood, these components are likely to serve an important role in providing pollinators with habitat [56] or urban food production [2]. Because species grown in urban agriculture tend to be pollinator-dependent and amenable to small spaces, they can form a network of biodiversity-supporting and food-producing infrastructure in urban areas [57].

#### 3.2.5. Social safety nets to support sustainable and healthy diets

Midday meals, the primary component of the Integrated Child Development Services (ICDS) programme, are an important and established pathway to food and nutrition security [27]. The meals are administered through a combination of actors including schools under the Ministry of Human Resources Development (MoHRD), Anganwadi Workers (AWW) under the Ministry of Women and Child Development (MoWCD), and ASHAs under the Ministry of Health and Family Welfare (MoHFW). Midday meals can be enriched with local fresh foods such as dairy, indigenous vegetables, and school garden produce to improve their nutritive value. Similarly, the Public Distribution System (PDS) under the Ministry of Consumer Affairs, Food, and Public Distribution (MoCAFPD) could also introduce fresh produce purchased from local farmers where feasible. In addition to these actions, the ICDS and PDS programmes could also work as pathways to educating women, children, and the general public about diet, nutrition and health. This could be done through occasional distribution of dietary supplements, or information leaflets about recommended nutrients and their sources in fresh food. The Women's Nutrition Programme (WNP) under the MoWCD currently only supports women of childbearing age, but could be extended to post-reproductive women to ensure better population health. The Poshan Abhiyan (National Nutrition Mission) under the NITI Aayog (formerly Planning Commission of India) currently monitors populations for deficiencies [58], but this programme could be modified to monitor nutritional adequacy to better reflect successes, shortfalls, and windows for intervention.

#### 3.2.6. The role of biodiversity in sustainable and healthy food production

The use of biodiversity resources such as wild forests, wild honey, and wild pastures forms an integral part of food production for some local communities. In some cases, provisions are already in place for such use, such as the Local Adivasi Multipurpose Cooperative Societies (LAMPS), and Joint Forest Management or Eco-development Committees, under certain State Forest Departments. However, resource allocation through Gram Panchayats, and spatiotemporal monitoring of resource health (in this case, bee populations) can be lacking, therefore resulting in overharvesting and subsequent decimation of the resource. The role of NGOs, Gram Panchayats, and LAMPS in training communities in sustainable harvest and monitoring resources is key to promoting sustainable use. In other cases, Gram Panchayats can similarly cooperate with the Ministry of Tribal Affairs, State Forest Departments, and NGOs to reopen traditional pastures to local communities for sustainable use (these have largely been banned since the Wild Life Protection Act of 1972). Invasive alien control strategy refers to clearing of invasive plant species, particularly in forests and wildlife areas, and it serves the dual purpose of improving ecosystem structure and function for indigenous biodiversity, as well as limiting pests and parasites that can spread diseases. Having prescribed protocol for such control, such as controlled burning, or biomass removal, which can be converted into value-added products such as small furniture or organic herbicide, opens up avenues for co-benefits of landscape management [59]. Biodiversity conservation includes the protection and propagation of local plant species that support pollinators in both rural and urban areas, and also those that feature in agroecological systems as traditional foods. This can be undertaken by local Biodiversity Management Committees (BMCs) in conjunction with farmers and the ICAR, KVK, MoA&FW, and NABARD, through seed banks and agroecological training.

#### 3.2.7. Market linkages to incentivise sustainable and healthy supply chains

Market linkages are an important pathway that can be leveraged to make sustainable and healthy foods more accessible and desirable to consumers, and more feasible to produce and sell for producers. Influencing consumer demand towards safe and local foods was identified as a pathway in its own right, because consumers are specific to the type of food (e.g. poultry, indigenous foods) or location (e.g. urban, ecoregion). Investing in supply chains for innovative and underutilised foods such as traditional vegetables and forest honey, through Local Adivasi Multipurpose Cooperative Societies (LAMPS), the Ministry of Food Processing Industries and the and the National Bank for Agriculture and Rural Development (NABARD) can help popularise these healthy, locally grown foods. Commodification of food and agriculture can reduce dietary diversity, nutritional security, and general wellbeing among agrarian households [7]. On the other hand, processing, packaging, and marketing of food can greatly influence consumer choices. Urban markets tend to have more disposable income to spend on new and convenient foods, making them an attractive proposition for innovative indigenous food products such as non-staple grain flours, dried mushrooms, local cheeses, and so on. This is likely to serve the dual purpose of opening up markets for both rural and urban agrobiodiversity, as well as making nutritious indigenous foods accessible to urban consumers [60]. Further, informative labelling on the farm origin and nutritional content of foods can also help drive consumer awareness and demand for locally appropriate, sustainably grown, and nutrient-dense foods, such as chemical-free millets [61]. The Ministry of Food Processing Industries together with businesses and the FSSAI would be instrumental in developing products, labelling, and market linkages to this end. It is acknowledged that commercialisation of agrobiodiversity may in some cases result in certain foods becoming less affordable for local communities, but we argue that domestication and cultivation is likely to overcome this issue.

### 3.3. Network of actors to implement actions

Various actors were identified at local (15), state (9), and national (19) level, who could be instrumental in the execution of the responses (Fig. 2). Farmers, consumers, and citizens were individual entities at local level that function as intermediates between institutional actors and actions. While all three could effect attitudinal change, farmers were much more connected to other food system actors and could also change processes, and consumers had some influence over capital through their market spending. At the local level, Municipalities emerged as the most impactful actors given their ability to effect institutional, capital, and process change (Fig. 2, Table a). ASHAs and NGOs were also highly connected actors, with the capacity to bring about attitudinal and process change by engaging with farmers, consumers, and the general public about sustainable and healthy food systems. Enterprises, Gram Panchayats, and BMCs had the leverage of capital to influence processes and attitudes, and LAMPS had moderate influence in areas with wild and agrobiodiversity.

State Departments of Horticulture, Forests, and FAHD can prescribe regionally appropriate measures for farming, agrobiodiversity, and animal husbandry. The Department of Horticulture could play a significant role in training farmers in sustainable practices and developing the various gardens described above. The Department of Education executes the midday meals scheme and school gardens, which cumulatively have a high impact on the environment-food-health nexus. Where applicable, state level organisations can commit to engage with farmers to educate them about farmer household nutrition, food safety and quality standards, and innovative market linkages. Extension workers from the departments of Agriculture, Horticulture, and FAHD would be pivotal to the delivery of these locally-specific services.

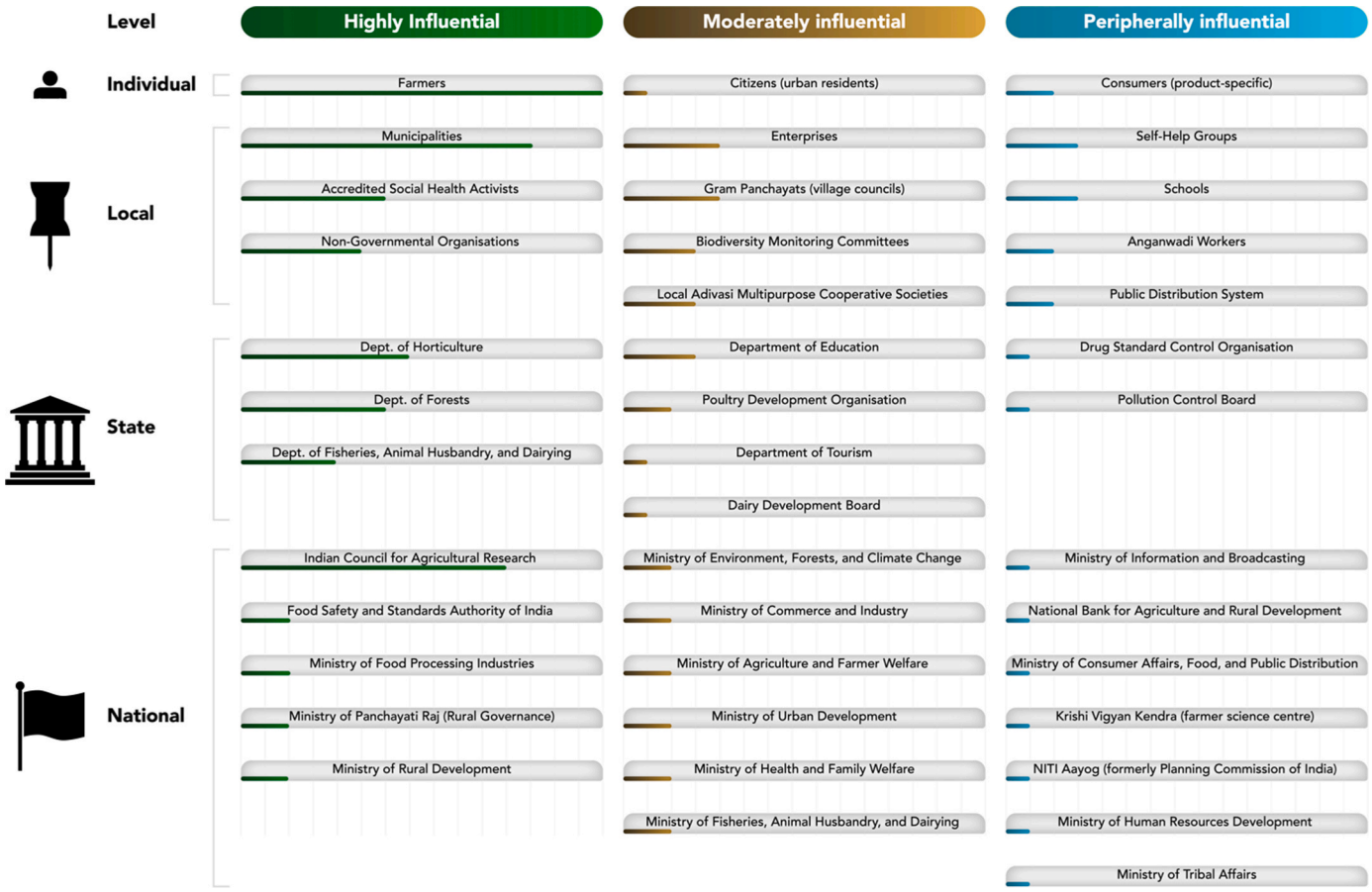


**Fig. 2.** Level of influence of actors across scales in food systems in India, derived from network analysis, scoring, and ranking (Table a). Colour fill represents degree centrality score, and ranking at each level is based on hub score and change score where the former is equal. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

At the national level, the ICAR and FSSAI emerged as impactful actors. The ICAR plays an important role in developing and disseminating farmer training through the KVKs. The incorporation of knowledge on sustainable farming practices and sustainable use of agrobiodiversity will be primarily operationalised by the ICAR. The FSSAI provides various levels of checks for food safety and quality, and their engagement with farmers will be instrumental in the uptake of safe and sustainable farming practices. The FSSAI also runs nationwide campaigns to raise consumer awareness for safe and nutritious food. These campaigns can help drive demand for better environmental food safety and local, fresh, foods. The Ministry of Food Processing Industries is a key player that can enable farmers to develop innovative food products and market linkages. The Ministry of Panchayati Raj (Rural Governance), through the Gram Panchayats, executes a number of the ongoing programmes and prescribed actions at local level as described above.

### 3.4. Policy implications

The policy implications from this study are likely to hold for a number of Global South food systems characterised by smallholder farming and urbanising economies. The findings suggest that devolution of sustainable and healthy food systems to the level of farmers and consumers is likely to have the most cross-cutting and synergistic outcomes for environmental sustainability, food production efficiency, and human health and wellbeing. This can be achieved by improving and updating food and nutrition education, enabling safe, sustainable, and nutrition-sensitive farming, and facilitating access to health and nutrition through social infrastructure like gardens and welfare programmes. In summary, the study recommends the following policy actions to streamline sustainable and healthy food systems in India and the Global South:

1. Engagement and education with the public around food safety, nutritious diets, and healthy lifestyles, through ongoing government nutrition and health programmes at national level. Public health centres, school feeding programmes, public broadcasts, and events organised in collaboration with civil society organisations will be instrumental in raising grassroots awareness of sustainable and healthy diets. In India, these would include the Poshan Maah and Poshan Jagruti Saptah events organised at village level, monitoring of population health through the Poshan Abhiyaan, and creating awareness through ASHAs, AWWs, FSSAI, ICDS, and PDS.
2. Developing farmer capacity to produce environmentally safe and sustainable food by scaling out ongoing pilot programmes on agroecology and circular economy, and indigenous and low- or no-chemical farming. Streamlining farmer extension services including training, finance, quality checks, and supply chain linkages through a nodal agency will make them more accessible and beneficial to farmers. In India, the ICAR and KVKs would play a central role in such streamlining of services, with the sectoral boards (e.g. dairy, poultry, pollution control) and the NABARD enabling development of sustainable infrastructure and supply chains.
3. Encouraging consumers and farmers to adhere to food safety standards is likely to have positive impacts on human health and nutrition and the environment where food is produced. Public engagement and farmer capacity building will synergistically influence markets for safe, sustainable, and healthy food. In this study,

the FSSAI, MoIB, and market actors emerged as the key stakeholders facilitating this aspect.

4. Promoting public food gardens in both rural and urban areas as living laboratories and demonstration sites for sustainable and healthy foods. These food gardens would reciprocate with public health and nutrition programmes, and add a layer of active involvement in environmental awareness and food sovereignty. The Ministries for Rural and Urban Development are the main actors involved in this action.
5. Updating government programmes to support public health, particularly for women and children, to transcend caloric sufficiency and address nutrition security. The impacts of a more holistic focus will benefit a wider section of a society undergoing a nutrition transition towards urbanisation. In India, existing programmes under the MoWCD should be expanded and adapted to present-day needs.
6. Working with communities and departments to better incorporate biodiversity into food systems to overcome the dichotomy between land sparing and sharing. Cross-sectoral support towards this end will combat on-farm and dietary monocultures, providing synergistic solutions for human health and the environment. In the Indian context, this requires collaboration between the Ministries of Agriculture and Environment.
7. Enabling market transition towards value-added nutritious and biodiverse food supply chains. The Year of Millets, a Government of India initiative, sets a valuable precedent towards this end. State Departments of Tourism can also play a role in promoting local agrobiodiversity through cuisine and experiential engagement.
8. Leveraging synergies between grassroots actors to implement locally appropriate interventions. Devolved food systems governance presents inroads to improved food sovereignty, nutrition security, and environmental outcomes.

### 3.5. Study limitations and further research

The study has limitations in its range of study sites, the small workshops involving researchers only, and the broad policy action recommendations. The study sites do not include important food producing areas in the Indo-Gangetic plains and other parts of India. Nevertheless, the diversity of social-ecological systems represented in the sample, coupled with the wide range of system stakeholders, allows for meaningful inferences and synthesis across scales. The policy impact pathways workshops followed an expert elicitation format, but did not include policymakers and implementers, or formal policy analyses such as ex-ante or cost-effectiveness assessments. This study is an initial exploration of proposed policy actions, and presents avenues and priorities for further research along the lines of governance co-production with policymakers and practitioners. Future research could include dialogue across scales and government and non-government sectors, scenario planning, and economic analysis (e.g. counterfactual, ex-post evaluations) of the proposed interventions.

## 4. Conclusion

Findings from this study indicate that public awareness and education, farmer capacity development, and food safety audits are crucial to making Indian food systems more equitable and sustainable. Findings also suggest that home, school, and public gardens can play an important role in improving access and awareness of nutritious and sustainable foods. Social safety nets like the ASHA, AWW, ICDS, and PDS continue to play a significant role in making food and health services accessible to a wide cross-section of Indian society. These could be further updated to extend awareness and access to sustainable and nutritious foods to promote healthy diets and wellbeing. Non-farm systems such as forests and pastures can be significant sources of nutritious foods, and land use policy surrounding these needs to be dynamic and adaptive so as to balance benefits and stewardship. Market linkages may be instrumental in bridging the areas of food safety and sustainability, nutritional sufficiency, and health and wellbeing. Findings also reiterate the importance and power of local-level actors in implementing policy and programme interventions and devolved governance.

## CRediT authorship contribution statement

**Mallika Sardeshpande:** Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Abi Tamim Vanak:** Writing – review & editing, Supervision, Funding acquisition, Conceptualization. **Akash Ashwini:** Writing – review & editing, Investigation, Data curation. **Chethana V. Casiker:** Writing – review & editing, Investigation, Data curation. **Hetal Hariya:** Writing – review & editing, Investigation, Data curation. **Ronita Mukherjee:** Writing – review & editing, Investigation, Data curation. **Suparna Chatterjee:** Writing – review & editing, Investigation, Data curation. **Pema Yangden Lepcha:** Writing – review & editing, Investigation, Data curation. **Durba Biswas:** Writing – review & editing, Supervision, Funding acquisition. **M. Soubadra Devy:** Writing – review & editing, Supervision, Funding acquisition. **Ankila J. Hiremath:** Writing – review & editing, Supervision, Funding acquisition. **Priyanka Jamwal:** Supervision, Funding acquisition. **Sarala Khaling:** Writing – review & editing, Supervision, Funding acquisition. **Siddappa Setty:** Supervision, Funding acquisition.

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## Declaration of competing interest

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

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## Appendix

**Table a**
Various levels of actors and their ranks, based on their degree centrality and hub scores in the network, and the sum of their impacts (1 = yes, 0 = no) on effecting Institutional, capital, process, and attitudinal change.

| Level | Rank | Actors | Network scores | | Change scores | | | | Total |
|---|---|---|---|---|---|---|---|---|---|
| | | | Degree centrality | Hub score (e−16) | Institutional | Capital | Process | Attitudinal | |
| Individual | 1 | Farmers | 15 | 10.6 | 0 | 0 | 1 | 1 | 2 |
| | 2 | Citizens (urban residents) | 2 | 1.77 | 0 | 1 | 0 | 1 | 2 |
| | 3 | Consumers (product specific) | 1 | 0.44 | 0 | 0 | 0 | 1 | 1 |
| Local | 1 | Municipality | 12 | 8.83 | 1 | 1 | 1 | 0 | 3 |
| | 2 | Accredited Social Health Activists (ASHA) | 6 | 5.3 | 0 | 0 | 1 | 1 | 2 |
| | 3 | Non-governmental Organisations (NGOs) | 5 | 4.86 | 0 | 0 | 1 | 1 | 2 |
| | 4 | Enterprises | 4 | 2.65 | 0 | 1 | 1 | 1 | 3 |
| | 4 | Gram Panchayats | 4 | 2.65 | 0 | 1 | 1 | 1 | 3 |
| | 5 | Biodiversity Management Committees (BMCs) | 3 | 1.77 | 0 | 1 | 1 | 1 | 3 |
| | 6 | Local Adivasi Multipurpose Cooperative Societies (LAMPS) | 3 | 1.77 | 0 | 0 | 1 | 1 | 2 |
| | 7 | Self-help Groups (SHGs) | 3 | 1.77 | 0 | 0 | 0 | 1 | 1 |
| | 8 | Schools | 3 | 0.44 | 0 | 0 | 1 | 1 | 2 |
| | 9 | Anganwadi Workers (AWW) | 2 | 1.1 | 0 | 1 | 1 | 1 | 3 |
| | 10 | Public Distribution System (PDS) Shops | 2 | 1.1 | 0 | 0 | 1 | 1 | 2 |
| State | 1 | Department of Horticulture | 7 | 4.41 | 1 | 1 | 1 | 0 | 3 |
| | 2 | Forest Department | 6 | 2.65 | 1 | 1 | 1 | 0 | 3 |
| | 3 | Department of Fisheries, Animal Husbandry, and Dairying (DoFAHD) | 4 | 2.21 | 1 | 0 | 1 | 0 | 2 |
| | 4 | Department of Education | 3 | 2.21 | 1 | 1 | 1 | 0 | 3 |
| | 5 | Poultry Development Organisation | 2 | 1.54 | 1 | 1 | 1 | 0 | 3 |
| | 6 | Department of Tourism | 1 | 1.99 | 1 | 0 | 0 | 1 | 2 |
| | 6 | Dairy Development Board | 1 | 1.99 | 1 | 0 | 0 | 1 | 2 |
| | 7 | Drug Standard Control Organisation | 1 | 1.1 | 1 | 0 | 1 | 0 | 2 |
| | 8 | Pollution Control Board | 1 | 0.66 | 1 | 0 | 1 | 0 | 2 |
| National | 1 | Indian Council for Agricultural Research (ICAR) | 11 | 0.66 | 1 | 1 | 1 | 0 | 3 |
| | 2 | Food Safety and Standards Authority of India (FSSAI) | 2 | 2.43 | 1 | 1 | 1 | 1 | 4 |
| | 3 | Ministry of Food Processing Industries | 2 | 2.21 | 1 | 1 | 1 | 1 | 4 |
| | 4 | Ministry of Panchayati Raj (Rural Governance) | 2 | 2.21 | 0 | 1 | 1 | 0 | 2 |
| | 5 | Ministry of Rural Development | 2 | 1.54 | 1 | 1 | 1 | 0 | 3 |
| | 6 | Ministry of Environment, Forests, and Climate Change (MoEFCC) | 2 | 1.32 | 1 | 1 | 1 | 0 | 3 |
| | 7 | Ministry of Commerce and Industry | 2 | 1.32 | 1 | 0 | 0 | 1 | 2 |
| | 8 | Ministry of Agriculture and Farmer Welfare (MoA&FW) | 2 | 1.1 | 1 | 1 | 1 | 0 | 3 |
| | 8 | Ministry of Urban Development | 2 | 1.1 | 1 | 1 | 1 | 0 | 3 |
| | 9 | Ministry of Health and Family Welfare (MoHFW) | 2 | 1.1 | 1 | 0 | 1 | 0 | 2 |
| | 10 | Ministry of Fisheries, Animal Husbandry, and Dairying (MoFAHD) | 2 | 0.88 | 1 | 0 | 1 | 0 | 2 |
| | 11 | Ministry of Information Broadcasting (MoIB) | 1 | 1.99 | 1 | 0 | 0 | 1 | 2 |
| | 12 | National Bank for Agriculture and Rural Development (NABARD) | 1 | 0.66 | 1 | 1 | 1 | 0 | 3 |
| | 13 | Ministry of Consumer Affairs, Food, and Public Distritbution (MoCAFPD) | 1 | 0.55 | 1 | 1 | 1 | 0 | 3 |
| | 13 | Krishi Vigyan Kendra (Farm Science Centre, KVK) | 1 | 0.55 | 1 | 1 | 1 | 0 | 3 |
| | 13 | Ministry of Women and Child Development (MoWCD) | 1 | 0.55 | 1 | 1 | 1 | 0 | 3 |
| | 14 | Ministry of Human Resources Development (MoHRD) | 1 | 0.55 | 1 | 1 | 0 | 0 | 2 |
| | 14 | Niti Ayog (formerly Planning Commission of India) | 1 | 0.55 | 1 | 0 | 1 | 0 | 2 |
| | 15 | Ministry of Tribal Affairs | 1 | 0.33 | 1 | 0 | 0 | 0 | 1 |

## Data availability

The data has been made available in the appendix

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