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Advancing urban sustainability transitions: A framework for understanding urban complexity and enhancing integrative transformations

Ying Li[1✉], Robert J. S. Beeton[2], Xiaofeng Zhao[3✉], Yeting Fan[1,4], Qingke Yang[1], Jianbao Li[1] & Linlin Ding[1]

Rapid urbanization and industrialization with their negative repercussions draw attention to the need for urban sustainability. This research built on the urban systems understanding linked with resource utilization, environmental effects, people-environment interactions, and adaptive management by integrating quantitative modelling of urban metabolism with a qualitative investigation into human responses. A hybrid methodology was applied in a typical industrial city of Jinchang, China, which exemplified a model of how complex urban dynamics link to and inform sustainability transitions. The study found that Jinchang City had taken on an unsustainable trajectory underpinned by continuous growth of material consumption, whereas a potential for sustainability transitions was also observed in decoupled negative material outputs, improved material efficiency, and environment regeneration collectively. The challenges in industrial cities have been framed in terms of development model lock-in, conceptual and institutional constraints, innovation and human capital deficiencies, and governance failure. The research proposed a government-led transformation system that integrates multi-level and multi-perspective transformations and management employing discipline insights to facilitate urban sustainability transitions. This involves governance, economic and technological innovations, social transformations, and implementations, in which urban governance and public engagement are essential elements for adapting to undesirable difficulties and exploring locally appropriate strategies. This research provided a theoretical and empirical basis along with scientific and policy implications, which contributed to the developing interdisciplinary knowledge on the understanding of complex urban systems and provided insights into real-world sustainability solutions.

[1] School of Public Administration, Nanjing University of Finance & Economics, Nanjing, China. [2] School of Earth and Environmental Sciences, The University of Queensland, Brisbane, QLD, Australia. [3] School of Public Administration, Hohai University, Nanjing, China. [4] The Key Laboratory of Carbon Neutrality and Territory Optimization, Ministry of Natural Resources, Nanjing, China. ✉email: yingli@nufe.edu.cn; zhao-xf@126.com

Introduction

Economic expansion, intensive resource usage, energy consumption, waste creation, environmental contamination, and accompanying social issues all occur in tandem with urbanization. Although urbanization is not the unique and direct cause to environmental issues, it will continue to have a profound effect on the natural environment (Bettencourt and West, 2010; Mumford, 1961), while ecological problems, social conflicts, health problems, and a slew of other negative consequences will occur if urbanization is not treated effectively (Asabere et al. 2020; Bateman and Hochman, 1971). Nonetheless, urbanization contributes to environmental conservation and social-economic prosperity by improved resource use efficiency and environmental management (Fan and Qi, 2010; Hui et al. 2023; Wang and Su, 2019). Cities are predicted to be utilized as major venues for creating issues and answers for huge environmental concerns and global sustainable development, as centers of human activity that directly and indirectly govern biophysical systemic changes (Angelo and Wachsmuth, 2020; Camagni et al. 1998; Elmqvist et al. 2019; Grimm et al. 2008; Repette et al. 2021; Yang and Zhao, 2023). These viewpoints are backed up by research from both established large cities and emerging cities experiencing significant expansion (Bai et al. 2010; Haas, 2012; Newton, 2008). The residents and administrations of these cities are confronted with a plethora of issues related to fast transformation. Cities would face shrinkage and unsustainability in the absence of rational planning and management, especially for many industrial cities (Li et al. 2016; Long and Wu, 2016; Wu and Wang, 2020). Most of these concerns are associated with the United Nations 2030 Agenda for Sustainable Development in achieving the SDG11 of sustainable cities and human settlements (Berisha et al. 2022; United Nations, 2015).

Sustainability research has been transdisciplinary and experienced a shift from protecting the environment and maintaining natural systems to social dimensions involving perception and values, behavioural options, governance, and politics (Loorbach et al. 2017; Wittmayer et al. 2016). It emphasises the cross-complementarities across the environmental, economic, and social dimensions, to illustrate complex systems, understand human-environment interactions, respond to realistic needs, and encourage a "revolution" in sustainability (Clark, 2007; Giddings et al. 2002; Kates et al. 2001). The concept of urban sustainability or sustainable cities has been as an essential subject in seeking global sustainability. Urban sustainability research is developing towards interdisciplinary research integrating the resources, ecology, environment, social and institutional aspects, which enlightens the importance of multiple approaches integration in research and practical world (Li et al. 2020; Ribeiro and Gonçalves, 2019; Spiekermann and Wegener, 2003). Transitions toward urban sustainability need to address the key issues framed in social and ethical considerations, technical capability, political and cultural settings, and knowledge-to-action linkages (Peter, 2021; Pira, 2021; Weinstein, 2010). It was acknowledged that the sociocultural environment has transcended the influence of the natural environment on urban development to dominate the interaction between people and urban systems. This implies that combining scientific research with governance aids in achieving sustainability objectives (Beeton and Lynch, 2012; Chan and Siu, 2015; Smedby and Neij, 2013).

Understanding how the urban systems work plays an essential role in promoting transitions toward sustainability. While a variety of methods and strategies have been employed to the understanding of urban systems and to support multifaceted urban transition initiatives, from conceptual framework building to urban systems modelling, spatial-temporal analysis, sustainability evaluation, transition governance et al., in context of diverse social-cultural-institutional background and perspectives (Chang et al. 2020; Mutisya and Yarime, 2014; Nevens et al. 2013; Turcu, 2013; Wamsler, 2015; Yin et al. 2023). Among the numerous studies, the urban metabolism models are widely adopted as approaches to simulate the operation of urban systems and find solutions to sustainable issues. The notion of urban metabolism views the city as an ecosystem where materials and energy circulate, are converted and used in different ways, and are subsequently released as waste, valuable products, or pollutants into the environment (Wolman, 1965; Girardet, 2014; Goldstein et al. 2013; Zhang, 2023). A highly efficient metabolism enables high rates of material reuse and recycling as a practical means of enhancing urban sustainability.

In addition to being a physical issue, urban sustainability has become more socially relevant, as cities are self-organizing entities that integrate the interrelated components of material distribution and social networks as they grow as coupled human and natural systems (Liu et al. 2007; Wong, 2021). Sustainable transitions have been a non-linear multilevel dynamic equilibrium transformation process that has a strong societal base (Loorbach et al. 2017). Multidisciplinary efforts have been made to attempt sustainable solutions that incorporate transitions from environmental preservation and resource conservation to social changes within a cultural setting (Hopwood et al. 2005; Todorov and Marinova, 2011). Many studies have endeavoured to advance urban transitions based on frameworks of sustainability, adaptation, and resilience et al. (Childers et al. 2014; McCormick et al. 2013; Nevens et al. 2013; Wang et al. 2023). There are few successful efforts and structural changes that have the potential to dramatically reorient urbanization toward sustainability (Castán Broto et al. 2019). The importance of human actions and initiatives that link with sustainable actions has been emphasised for urban transitions, which calls for bottom-up, participatory, and negotiated approaches (Neuhoff et al. 2023; Turcu, 2013). Consequently, finding solutions for sustainable urban transitions involves more consideration of governance, social factors, and their practical applications (Chan and Siu, 2015; Colantonio and Dixon, 2011; Ernst et al. 2016; Sareen and Waagsaether, 2023; Weinstein, 2010).

Despite notable transformations in the urban sustainability paradigm, there is a relative paucity of systematic research on sustainability transition that combines knowledge of urban physical and social systems with strategic responses to sustainability concerns. Especially less attention has been paid to the effects attributed to social elements and human responses, which are critical to the practical dimensions of sustainable transitions. These concerns bring a sense of urgency to understand the complex urban system, by answering questions of how the urban biophysical system works, how humans act in the urban social system, and how to facilitate urban sustainability transitions in regional resource-environmental and socio-economic status quo. Therefore, our research was organized to address the issues above. The main objective of this research is to gain deeper insights into urban systems and seek possibilities in societal regimes for urban transitions toward sustainability.

To support the theoretical and analytical arguments, our study took Jinchang City, a natural resource-dependent industrial city in China, as an example to gather empirical evidence. With the advancement of the global sustainable process and the increasing prominence of the historical legacy of resource cities, most of the resource cities are facing a series of sustainable development problems. The intensification of conflicts between resource dependence, ecological environmental protection, and economic and social development has aggravated the problems of sustainable development in these cities. Environmental management plays a critical role in promoting sustainability transitions (Mosgaard and Kristensen, 2023). This is especially true for industrial cities in fast-growing nations, where the externalities of industrialization and urbanization have a major influence on citizens and urban natural systems (Dong et al., 2016; He et al., 2017). This challenge of sustainability transition is global, but industrial cities in particular offer appropriate opportunities to test innovative systemic changes.

Our research places a premium on sustainability theories, a knowledge of urban systems including subsets on urban metabolism and social systems, and adaptive strategies to urban sustainability transitions. Our interdisciplinary perspectives are conductive to deepen the understanding of urban sustainability and explore the social relevance of urban transitions that consider the complexities inherent in the real world. The research contributes to transcending knowledge gaps and advances the scientific discourse of urban sustainability transitions in the following aspects: a hybrid methodology for a systematic knowledge of complex urban systems by linking urban metabolic dynamics with human response, and an innovative framework of urban sustainability research by integrating grass-roots initiatives in research paradigm and multi-perspective adaptive strategies. The research findings would enhance the understanding of the complex socialized urban systems, and provide important insights about how to handle such shifts toward urban sustainability. It also has broader ramifications for other regions of the world that are going through comparable trajectories.

Theoretical framework and methodology

Conceptual framework. The central hypothesis of this study is that transitions to urban sustainability might be facilitated by better urban environmental management informed by the optimization of urban biophysical structure with high efficiency of material flows, along with a wider public exploration as to how the urban social systems function. This was based on two theses leading the literature to research questions. First, understanding the complex urban dynamics is of importance for urban management; Second, urban transitions toward sustainability are dependent on integrated transformations that are culturally and politically appropriate. To explore these, three research questions (RQ) were developed to guide this research: RQ 1: How can urban metabolism be applied to understand urban biophysical systems? RQ 2: How to understand the urban social system of human-urban interaction in the context of sustainable urban development? and RQ 3: How can urban transitions toward sustainability be facilitated? These questions were resolved by using a holistic strategy that incorporates a variety of approaches that are applicable to various parts of the study.

In the field of discovering how humans change and adapt to the urban environment, human-environment interactions have become an important issue that reveals the dynamics of the complex systems of cities (Fig. 1). In the complex urban physical-social system, the human response is in the pivotal position linking the urban physical system and the human-social system. The relationship between the human response and the urban physical system is based on material sourcing and environmental dependence. While the value orientation of human response depends on the norms and institutions of the human-social system. High efficiency of urbanization and environmental-friendly ecologicalization facilitate cities to address the resource and environmental crisis. In this course of transition, there is an increasing emphasis on the importance of the fundamental role of urban environmental systems and suggests integrated urban management systems that incorporate environmental principles into social and economic decision-making through positive human responses.

This study adopted systems thinking to comprehend and manage dynamic urban systems in the context of China's adaptation to its changing environment. Systems thinking along with multi-level viewpoints that emphasize the interrelationships among the major variables of a complex system were required to consider the urban system as a full entity with multi-level interactions. It offers a framework for researching complex and multi-faceted urban systems and improves decision-makers' capacity to implement successful strategies and actions.

The DPSIR (Driver-Pressure-State-Impact-Response) model was used as a framework for urban research in this study (Fig. 2). This model was designed to identify causal linkages between human activities and the urban environment. It may be used to assess the status of the environment, assess human responses, and aid decision-making (EEA, 1999; Liu et al. 2019; Tscherning et al. 2012). In particular, the phase of response could be directed at any previous phase and motivate substantial changes.

According to the DPSIR model, human activities put strain on natural resources and the environment, and these pressures influence the quantity and quality of the natural environment and people. Policies, rules, planning, and individual behaviour are used by governments and communities to adapt to these changes (Ness et al. 2010). Based on the causal linkages between human activities and natural, societal, and environmental changes, the model could inform effective actions that may decrease or avert negative pressures and repercussions.

Case study. Empirical case study research is critical for addressing the complexities inherent in examining substantive and real-world topics (Robson, 2011). Jinchang City, a mature resource-dependent industrial city recognized by the State Council in 2013, was used as a case study in this research. The city is in the Hexi Corridor in Gansu province of north-western China. It is China's top producer of nickel and cobalt, as well as a refiner of platinum group metals. The city's output of nickel and platinum group metals accounts for 90% of China's total production.

Jinchang City has been growing rapidly since 1959 following the discovery of a nickel mine located at Longshou Mountain in the west of the city. The first inhabitants of the city were the immigrants from neighbouring cities and rural areas, as well as young intellectuals and decentralized cadres from eastern China. Natural resource-dependent industries are the key to Jinchang's economy. Over the past two decades, Jinchang City's GDP had an average annual growth rate of around 12%. By the end of 2022, the city had a population of 209,950. The gross domestic product (GDP) achieved 32.8 billion yuan (CNY), with the industrial added value accounting for 77.6%. The GDP per capita reached 125,542 yuan per year, which was much higher than the Chinese average (85,698 yuan per year) and the Gansu provincial average (44,968 yuan per year).

Cities with a substantial industrial component usually transition over time from a focus on fast development with major negative effects on the environment and people, to a phase of recovery and then to a maturity or irreversible decline. As one of China's 126 resource-dependent cities, Jinchang City is currently in a fast-growing phase. However, its fast development of both industrial output and urban construction comes with related negative externalities. In 2004, it was one of the ten most polluted Chinese cities. The constraints of resources, environmental deterioration, and people's increasing demand for a better environment, have prompted the city to change its brutal way of development in the past. How to avoid urban decline and regenerate cities toward sustainable development is of great

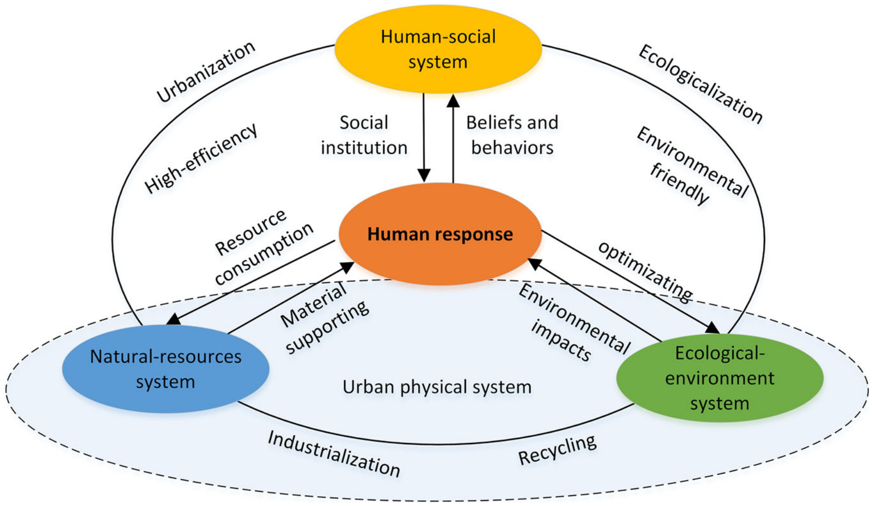

Fig. 1 Theoretical model of the complex urban physical-social system.

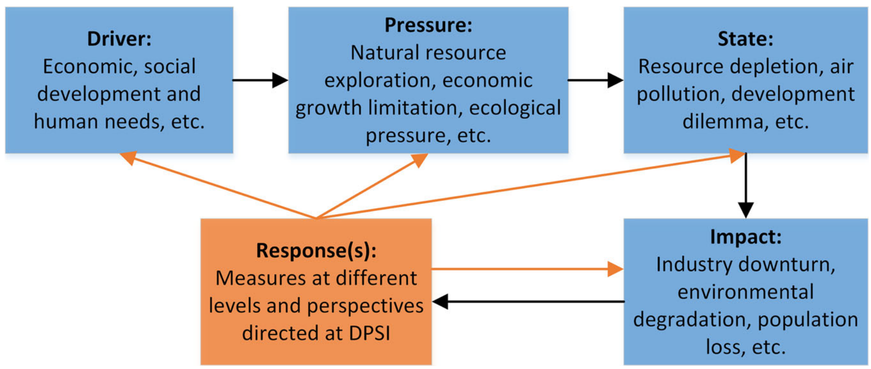

Fig. 2 Conceptual framework of DPSIR model.

importance to Jinchang City. Whilst, this combination of circumstances makes the city an ideal case study for emerging industrial cities seeking paths to a long survival. The exploration of a sustainable urban development path for Jinchang provides an experiment in making a smooth transition that will be relevant to many other industrial cities, and cities similarly constrained in their development by resource and environmental constraints, in China and around the world.

Methodological Procedure. This research, which considers cities to be hybrids of biophysical and social systems, focuses on the quantitative modelling of urban metabolism and the qualitative investigation of the human-urban interaction of Jinchang City. For a more comprehensive knowledge of urban processes, many analytical methodologies were used in conjunction with one another (Fig. 3).

Quantitative research techniques were utilized to explain correlations between variables, establish a visible numerical backdrop of urban systems, and draw judgments using quantitative statistical analysis. Energy and materials go through the urban metabolic system, where they are converted and used in different ways before being released as waste, useful products, or contaminants into the environment. This research treats the metropolitan system as a "black box" and only considers material inflows and outflows, ignoring internal dynamics. The material inflows in Jinchang City mainly included industrial minerals and metals, energy consumption, construction materials, and biomass. Each major category includes many types of material inputs. Such as industrial minerals and metals were composed of total mining minerals, imported metals, and chemical materials. Energy consumption consisted of coal, coke, heavy oil, diesel oil, petrol, and electricity. The material outflows consisted of industrial products, solid waste, water pollutants, and air pollutants, while the air pollutants were measured by SO_2 emissions, nitrogen oxides, and dust.

In this study, material flow analysis (MFA) was applied to open the "black box" of urban metabolism by transforming the actual urban system into a collection of numerical quantities that can be readily comprehended (Goldstein et al. 2013). Although MFA was first applied in the social and economic spheres, it is now being used more and more to comprehend the intricate relationships that material flows have with the environment in urban systems (Fischer-Kowalski, 1998; Nong et al. 2023; Schandl and West, 2012). This method of investigating resource metabolism in economic and industrial operations permits the evaluation of resource utilisation efficiency. Then the urban system's sustainability was assessed utilizing decoupling approaches (Fischer-Kowalski and Swilling, 2011; OECD, 2002; Tapio, 2005). The decoupling model uses a "flexible concept" to reflect the decoupling relationship between variables, to evaluate the potential of urban sustainability. The elasticity value of "*T*" was used to measure the decoupling relationship between material flows and economic growth and indicate the potential of urban sustainability.

$$T_{MF,GDP} = \frac{\%\,\Delta \mathrm{MF}}{\%\,\Delta \mathrm{GDP}} \tag{1}$$

in Equation 1, $T_{MF,GDP}$ represents the decoupling elasticity between material flow (material inflow or outflow) and economic growth;

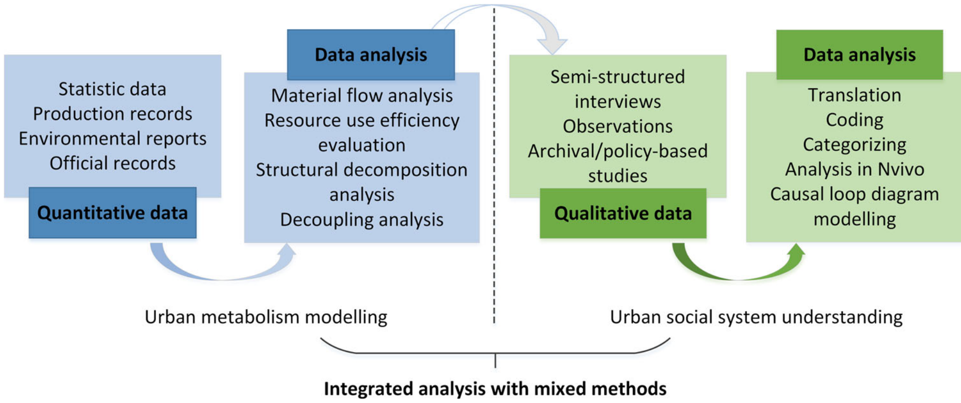

Fig. 3 Mixed analytical methods for urban systems understanding.

ΔMF and ΔGDP refer to the changes of material flow (material inflow or outflow) and GDP respectively. Decoupling status in a given period depends on the value "T" ($T < 0$, $0 \le T < 0.8$, $0.8 \le T \le 1.2$, or $T > 1.2$) and the changing trend of MF and GDP ($\Delta MF > 0$ or <0, $\Delta GDP > 0$ or <0). There are 8 decoupling states based on three basic states of negatively decoupled, decoupled, and coupled.

Qualitative research methods were adopted to interpret the urban social structure. To gain a bottom-up understanding of the real world, semi-structured interviews with representatives of local government, corporate, and civil society were conducted. The main goal of the interviews was to gather knowledge and insights from the target population that are pertinent to the research questions. The findings of the qualitative investigation were applied to identify sustainability issues, determine the roles of various stakeholders, triangulate our understanding of urban systems and human reactions, and offer tactics for incorporating human elements in decision-making. These helped to understand human-urban system interactions and some fundamental concerns driving sustainable urbanization. It defined the nature of the urban system, provided complementing knowledge of the actual world, and suggested a potential for public engagement in sustainable urban administration. Specifically, certain public inquiry data helped clarify and filter complicated and contradicting data, allowing for a better knowledge of urban processes. With a focus on improving urban sustainability, this research built an improved urban environmental management system by combining top-down and bottom-up approaches. The synthesis of top-down and bottom-up techniques is beneficial to environmental management since they complement one another (Böhringer and Rutherford, 2008; Harder et al. 2014). The semi-structured interview materials were open-coded and categorised to build the qualitative data structure (Corbin and Strauss, 2015; Yin, 2009). These were then linked into nodes to create causal loop diagrams (CLD) for representing human-urban system interactions.

It is possible to acquire a more complete knowledge of urban systems by combining various methodologies and avoiding biased outcomes by presenting multi-angle evidence. In two related studies, detailed analytical approaches aimed at urban metabolic modelling (Li et al. 2016) and urban social system comprehension (Li et al. 2019) have been outlined and tested, and those will not be elaborated tautologically here.

Data sources. Multiple data-gathering approaches that complement one another are required to gather sufficient information and prevent biased outcomes to solidify the framework. A variety of data collection techniques were employed in this study, including documentation of literal and numerical documents from various sources, semi-structured interviews with questions aimed at gathering consolidated information from the target population, self-reporting of personal feelings, attitudes, and beliefs via a field log book, and visual evidence through observation as an essential complementary approach to gathering evidence. All these methods were used to gather data for this study.

Statistical Yearbooks of the city, a collection of major manufacture's records of production, environmental statistical reports, and environmental monitoring records were sources of quantitative data. Official reports and network databases, such as China's environmental quality report, were used to supplement the original data. Semi-structured interviews were the main sources of qualitative data. As a result of the interviews, open-ended replies and follow-up questions were used. Four groups of people, including representatives from the government, business leaders, manufacturing employees, and ordinary residents of the city were consulted. The identical questions were asked to each informant, and the sessions lasted around an hour each.

Urban system understanding

Urban biophysical system modelling. The material flow analysis between 1995 and 2020 in the case study city indicated that the urban metabolism of the city was characterized by high levels of material consumption and waste generation, posing significant challenges to urban sustainability (Fig. 4). However, during the two decades of accessible data, the implementation of MFA and accompanying analytical approaches enabled knowledge of the concrete causes of deterioration in the face of increased output. Over the studied period, Jinchang City's material inputs and outputs showed a scenario of high resource consumption, with the total volume quadrupling from 5.24 million tonnes to 20.67 million tonnes. The consumption of industrial minerals and metals increased from 2.24 million tonnes to 12.26 million tonnes, reflecting an increasing scale of production. It was also observed that the share of energy consumption kept decreasing, while the share of industrial minerals and metals in total material inputs continued to rise. The trend of declining energy usage per unit of metal production demonstrated the increasing efficiency of industrial production.

During the same period, the major pollutant of sulphur dioxide accounted for 60–75% of total air pollution, but its emissions have been decreasing as production scales expand. The SO_2 emission per unit of industrial product outputs has declined from 3.34 to 0.10, indicating an effective SO_2 reduction from the existing production and restraint from the enlarged production. In addition, the increase in nitrogen oxide emissions reflected the

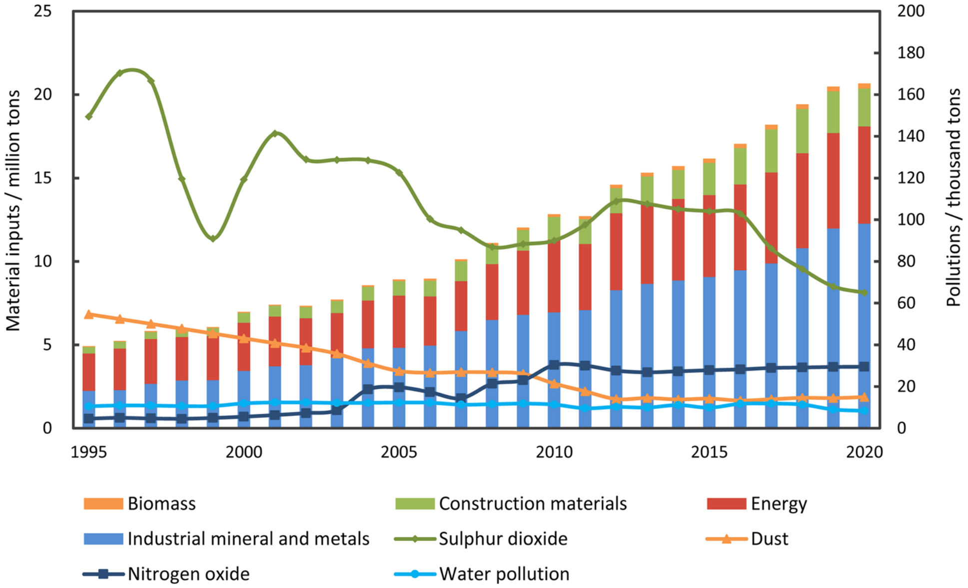

Fig. 4 Material inputs and main pollutants in Jinchang City.

improvement in household income and the associated increase in private cars in Jinchang City. The fast increase in automobile ownership since 2008 has countered the beneficial effects of renewable energy adoption and vehicle emission control systems. Meanwhile, the dust declined continuously from 54.66 thousand tonnes to 14.96 thousand tonnes during the studied period. This corresponded with environmental regeneration involving extensive tree planting, ground stabilisation, and landscape renovation around the urban area to reduce ambient dust, and the utilisation of industrial dust removal techniques in both production processes and winter heating systems.

Despite a large dependence on material/energy consumption and the complexity of environmental concerns, sustainable tendencies have been observed most notably economic development being significantly decoupled from SO_2 emissions. This supported the hypothesis that enhanced resource use and environmental circumstances, when combined with prudent investment, would enable urban sustainability transitions. The correlations between GDP and material inputs-outputs shifted often and tended to be decoupled, showing increased material/energy efficiency and improved environment (Fig. 5). This featured advancements in technology and industrial restructuring aimed at changing the trajectory of economic growth. There could be a chance that other variables will decouple later when SO_2 emission undergoes a strong decoupling. Positive developments represented the benefits of pollution control investments, industrial technological advancements, and urban economic structural adjustment. The findings also confirmed the approach's use for tracking progress toward a more sustainable city.

Jinchang City's economy is primarily reliant on mining and mineral processing, which directly contradicts urban sustainability. However, improvements have been proven to be achievable via creative investment, the adoption of cleaner manufacturing in conjunction with circular economy techniques, and structural reforms to the economy. Total air pollution has significantly decreased in recent years, owing to increased industrial output, economic expansion, and household spending. Additionally, major advancements in water quality, water reuse, and eco-environmental conservation have occurred. Simultaneously, societal wealth has multiplied several-fold. Taken together, this demonstrates significant progress has been made in the urban economy, society, and environment, implying that urban sustainability is theoretically attainable.

In addition to what the data shows, it is worth noting that there is a wide range of viewpoints on the problem of air quality, which is directly related to the urban environment. When it came to the environmental costs of air pollution, health was the most important issue. Most of the residents acknowledged the visible progress in environmental improvement over the last decade, yet a few insider anecdotes provided important facts that contradicted official claims. The investigation uncovered a discrepancy between people's subjective perceptions and government statistics on pollution emissions. Residents in the area have reported seeing emissions in the dark of night, suggesting that the officially recorded pollution levels may have been higher than they really were. According to this implication, the information provided by local governments and businesses was subject to debate or error. The MFA modelling revealed that the favourable trend in the urban environment found should be considered with caution. This emphasizes the importance of using a variety of approaches to get a comprehensive understanding of a given scenario.

Urban social system of human-urban interaction. Understanding the urban social system in the context of sustainable development was facilitated by the modelling of causal relationships between humans and urban systems. It revealed that stakeholder commitment, institutional development, and personal development are the three main clusters that determine how urban social systems influence sustainable urban development. These entwined components contribute to the formation of an integrated metropolitan social system with many feedback loops (Fig. 6).

Numerous governmental and societal issues are linked to institutional constraints. The key to boosting institutional development is reforming governance evaluation, building decision-making capacity, and improving decision-making processes. Unblocking GDP-based "yardstick competition" on urban governance is critical, as is improving the efficacy of plan execution by boosting decision- and policy-makers' capabilities. In addition, stakeholder engagement in decision-making is critical to balancing interests and creating a knowledge basis for sustainable urban governance.

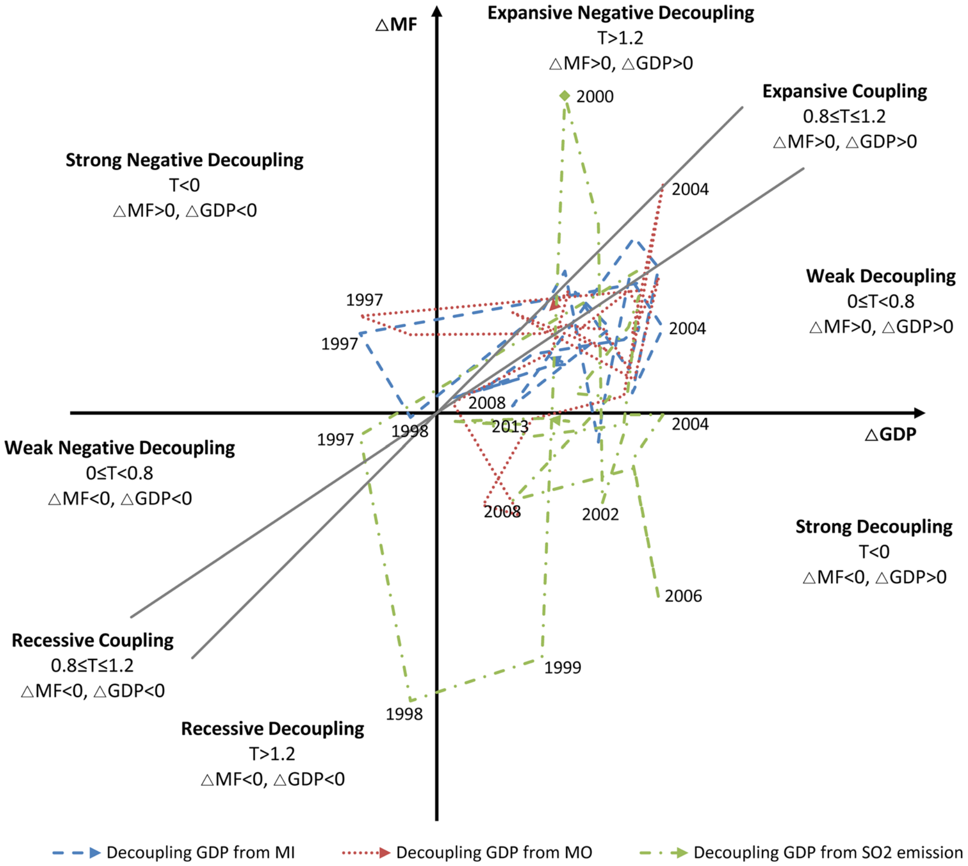

Fig. 5 Decoupling economic growth from material inputs and material outputs factors.

Government commitment is critical in conducting and coordinating urban environmental management via a variety of measures. The ability of local governance to integrate various and multi-level resources and strengths is essential for fostering departmental collaboration, bringing together specialists from many disciplines, and including the public in decision-making processes. Government informants generally had a more positive perspective on the economy due to their specialized knowledge and the fact that they had prioritized economic transformation in the work routine. Those who were less optimistic about the economic transition said that a better urban environment and a sustainable economy should be the government's two major considerations. Because of this, the local government was expected to make wise decisions and assist in the execution of plans. Moreover, collaboration between government and business, as well as public engagement in urban governance, are critical for innovation and knowledge-based policies. Notably, public engagement has become a critical component of environmental decision-making since it helps explain local issues and promotes a commitment to sustainable urban management. However, the obstacles to establishing a participatory decision-making process centre on overcoming the communication framework's deficiencies and the local citizens' inadequate desire to participate. To address local environmental concerns brought forth by the public, this calls for local governments—or ideally national levels of government—to define cooperative mechanisms and offer fundamental support for public participation.

There are several ways in which people's efforts might impact their pro-environmental behaviour and performance. When they are combined with cultural development, which helps people grow by giving them moral support and a positive social environment for pro-environmental behaviour, they make up an important soft power foundation for sustainability transitions. Although the local people's self-assessed level of environmental consciousness was low, their expectations for the sustainability of urban futures were higher. Local people's attitudes and lifestyles impact their real actions in decision-making and everyday behaviours, and bridging the gap between knowledge and practice is a critical problem for the development of pro-environmental behaviour. This demonstrates that people's actual behaviours are often inconsistent with their beliefs due to the need to make trade-offs. Intellectual capital, as the primary source of information and experience, facilitates pro-environmental behavioural adaptation in administrative choices and everyday life by increasing stakeholder understanding, motivation, and commitment. Enhanced policy interventions via education, training, information distribution, and talent introduction tactics, together with better social and environmental infrastructure, might help individuals acquire pro-environmental behaviours.

Integrative transformations toward sustainability

In addition to the conventional fundamentals and goals of urban sustainability, the residents also have their own opinions and aspirations for sustainability. They emphasized on issues related to the habitable environment, improved living standards, social harmony, and civilized behaviours (Fig. 7). Higher standards of living, a liveable environment, social peace, and civilized behaviours were of the utmost significance to local inhabitants. People's sense of happiness is ingrained in sustainability since the word "happiness" was applied a lot. It was also reported by several informants as "feeling better" or as a "comfortable smile". Each facet of urban sustainability is defined by a set of norms that informants feel necessary. These grass-roots perspectives offer an objective orientation for the urban sustainability transition.

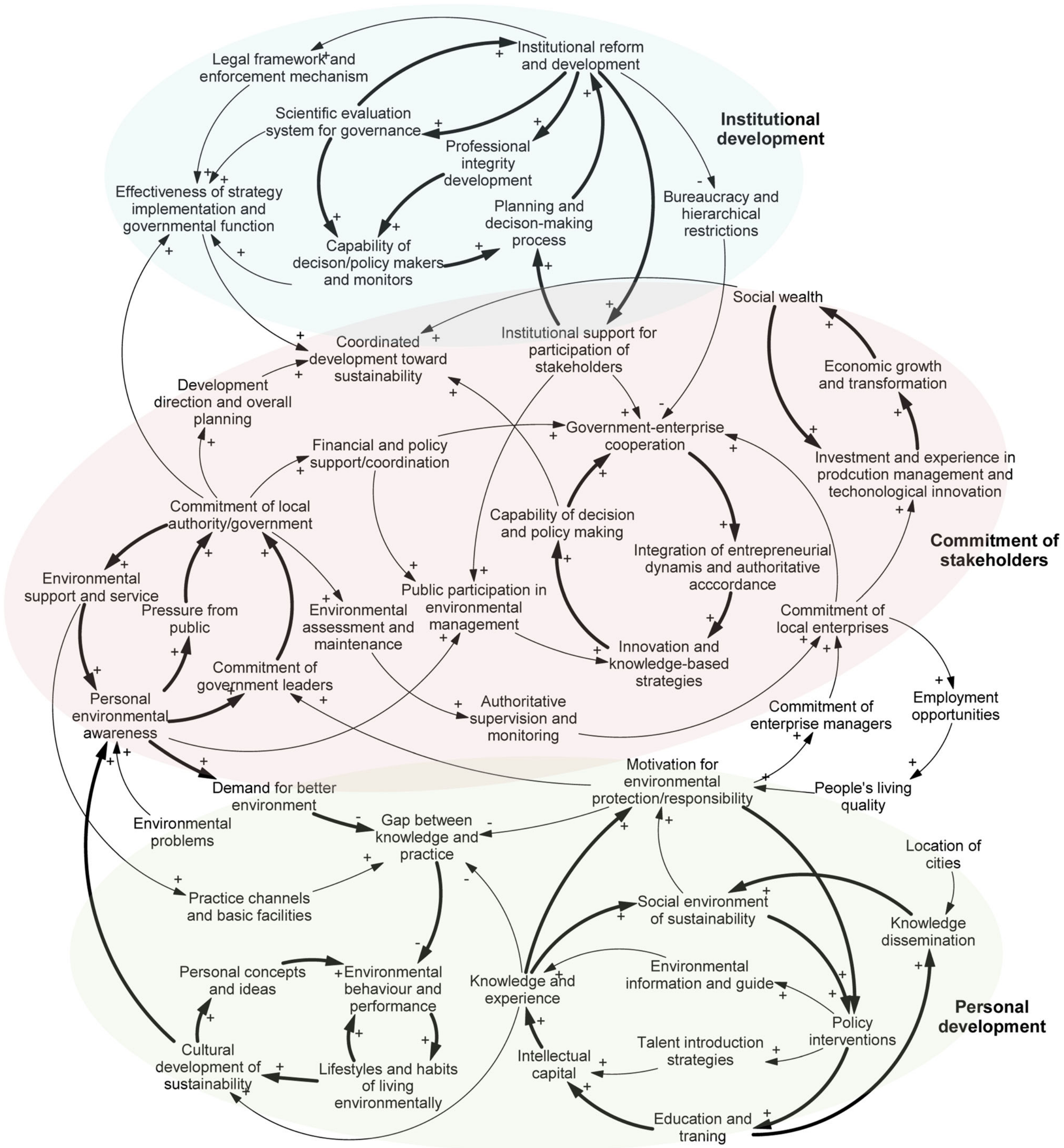

Fig. 6 Key social factors reflecting the human-urban interaction in urban social system. Source: Adapted from Li et al. (2019). Note: positive (+) and negative (-) arrows demonstrate reinforce and reverse feedbacks between variables.

To facilitate urban transitions toward sustainability, adaptive policies, and creative thinking are needed to enhance decision-making mechanisms in dynamic urban systems, which are always confronted with new difficulties (Beck and Conti, 2021). It takes into consideration a variety of choices made by many actors from the public and corporate sectors, as well as civil society. However, initiatives that have the potential to transform people's behaviour and society were few. It was believed that a government-led integrated decision-making and regulatory framework suited to the specific context should be developed. In this framework, multiple goals of economic, environmental, and social sustainability, as well as their interconnections, need to be considered throughout the decision-making process to arrive at more effective solutions. It is concerned with innovations and adaptations in governance, planning, and social management as they relate to the development of cities. Governance and public engagement are two critical and interdependent variables that impact decision-making and strategy implementation in this procedure (Li et al. 2019). At their nexus are the well-recognized techniques for enhancing environmental outcomes.

To be sustainable, cities' dynamic systems must be continually improved and adapted to new conditions. This requires a thorough comprehension of urban dynamics, as well as adaptive reactions and a variety of techniques to deal with the city's

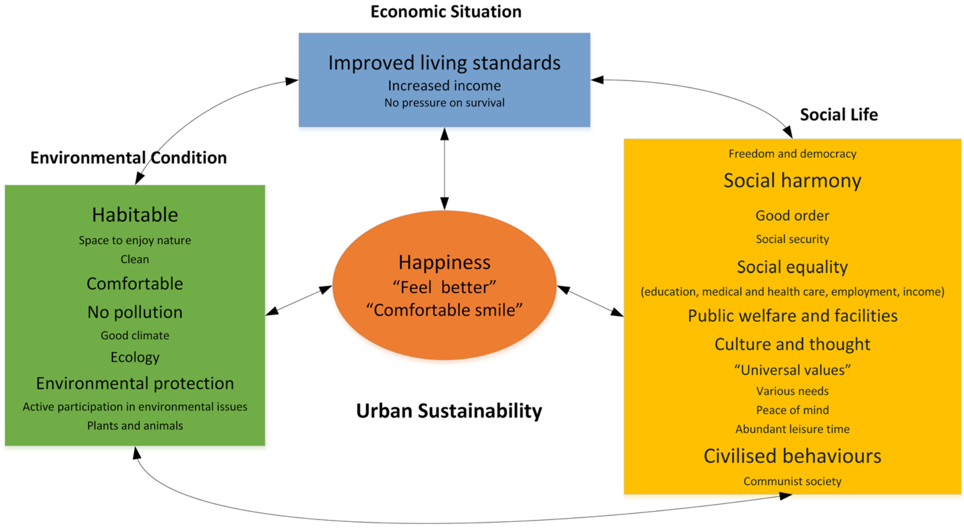

Fig. 7 Informants' descriptions on the structure of urban sustainability formulation. The font size is based on the frequency of words spoken by the interviewees while discussing their views on sustainable urban development.

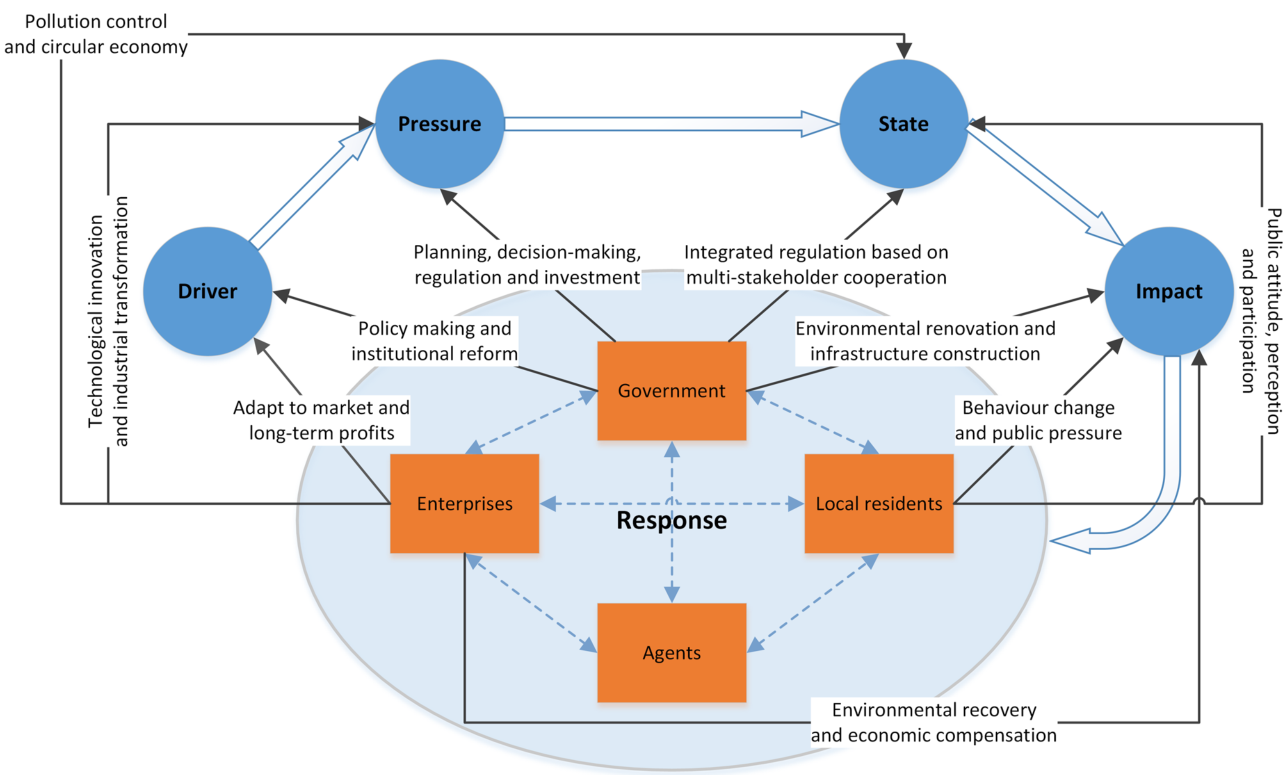

Fig. 8 Adaptive responses (R) of stakeholders to urban DPSI.

challenges. Challenges in sustainable urbanization are presented due to institutional limits, economic growth patterns, and innovation and intellectual capital deficits as well as a lack of public engagement in both decision-making and everyday performance, as established in the previous research. Multi-level reforms and their synergy across levels are needed to strengthen governance and innovation in both the economy and the environment, as well as to incorporate people's lives into a sustainable society. Fitting the study's findings in the DPSIR framework, it showed the reaction component with the adaptive responses of various stakeholders (Fig. 8). In the framework of the social system, responses are diverse and geared toward the other four stages. This depicts the reaction process that results in solutions aimed at reorienting urbanization toward sustainability.

These reactions engage in a variety of activities and interactions. It points to a system of integrative transformations driven by the government that is appropriate to the local setting. This solution is designed to integrate multi-level and multi-perspective innovation and adaptive management employing discipline insights (Fig. 9). More flexible combinations of institutional and economic transformation, eco-environmental reconstruction, human initiatives, and social transitions are needed to establish transitional paths. These factors propose primary paths for urban transformation planning and execution. Interactions between

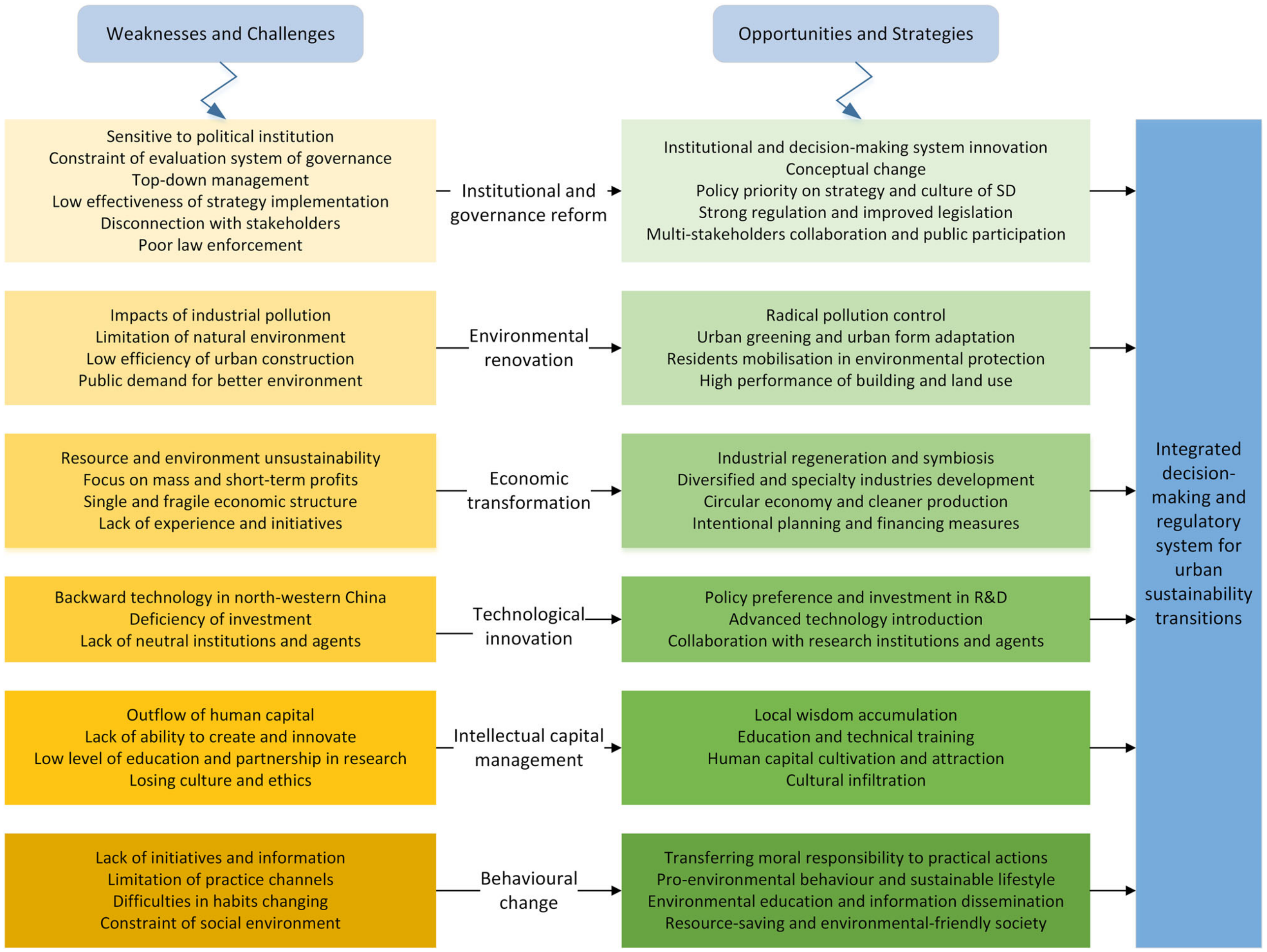

Fig. 9 A system of integrative transformations for urban sustainability transitions.

these strategic choices are especially critical, since physical changes in urban metabolism are pertaining to economic activity, environmental circumstances, and social dimensions (McCormick et al. 2013).

As a typical industrial city with a sound economic basis, Jinchang City can use the advantages of specialist industries to revolutionize urban environmental management and promote sustainable urbanization. To efficiently accomplish environmental goals while also adapting to local conditions, it is critical to integrate multi-perspective thinking and public engagement. This implies that all tactics should be employed contextually. Economic growth may reorient itself toward more efficient, clean, circular, eco-friendly, and diverse development. This might be facilitated through strengthened governance and multi-stakeholder participation, as well as expanded efforts and capacities of decision-makers. Local governments could set locally appropriate goals and strategies based on the actual state of the urban system and coordinate multi-level choices. The government is required to take proactive measures to identify crucial urban transition touch-points, define realistic targets, stimulate economic transformation and diversification, delegate authority, and support plan execution progressively. This requires an enhanced environmental management system that is based on integrated decision-making and regulation, organized around accountable departments and agents, promotes cooperation and supervision, and inspires public enthusiasm and involvement within a cultural context of harmonious development. In north-western China and similar less-developed regions, challenges in ideological transformation, economic structural adjustment, and intellectual capital management are crucial to local development, which may be facilitated by education, targeted incentives, and preferential policies.

Discussion

Research implications for understanding urban system and urban sustainability. Our study, with a focus on the specific challenge of a resource-dependent city in northwest China, provided broad research implications for enhancing the understanding of coupled human-nature urban systems and urban sustainability of industrial cities in general. In the succeeding industrialization and urbanization processes, negotiating the trade-offs between sustaining the environment and maintaining economic growth toward improving human well-being is the principal sustainability challenge in industrial cities. The urban metabolism of the industrial city of Jinchang generally shifted from high resource dependence to high material and environmental efficiency. Synchronised progress in economic development and environmental improvement requires radical transformations of dematerialisation and decoupling of economic growth from material consumption by adopting technical approaches of cleaner production, circular economy, and economic structural adjustment. Nevertheless, its sustainability potential needs to be supported by broader transformations in the social dimension that determines the mechanisms of human-environment interactions. Yet, this urban sustainability challenge is far from being addressed.

Since the city is an environment-based social-economical system, our research demonstrated that an integrative transition with a holistic view is needed for urban sustainability rather than a collection of one-off initiatives, which are in line with those of previous studies (Dendler et al. 2012; Geels, 2011; Smith et al. 2010). The change necessitates integrated management rather than an understanding of discrete indicators or single parts of sustainable issues. This requires a wide range of viewpoints, techniques, and management to grasp and explore real-world solutions. Our study found that locals' requirements and opinions toward the urban environment varied, and some revealed necessary information conflicting with the official statements. This highlighted the importance of public investigation and calls for attention to the value of grass-roots information and initiatives in real-world research. Our study suggested that it is impossible to accomplish a complex urban transformation with a single action, but involves adaptive solutions at several levels. This process of generating integrated and targeted tactics entails an ongoing examination of complementary and competing routes, drawing on the merits of a variety of models.

Our empirical study demonstrated that industrial cities could be more environmentally friendly as the city tends to mature and regenerate. Such a scenario is already possible that greatly improved urban conditions are emerging in some cities in developed countries, where environmental regulation and better technology are dominant (Beeton and Lynch, 2012). This means that cities may and should play a key role in assisting the transition to sustainable development. Our study emphasised the importance of considering integrated approaches and regulatory systems informed by a systematic understanding of the socialized urban systems. It projected a possibility of achieving a dynamic equilibrium between economic, environmental, and social advantages via urbanization that is sustainable. Consistent with Purvis et al. (2019)'s opinion, our research argued that transitioning to a more sustainable urbanization entails looking at the three-pillar system of sustainability from a holistic and local perspective and developing solutions that benefit all. Urbanization is shifting toward sustainability, with increased contributions from economic growth, capital accumulation, technological innovation, public engagement, and developing theories and practices of sustainable development. There are similarities between the attitudes expressed by Clune and Zehnder (2020) who claimed that sustainability solutions integrating good governance, technology implementation, and market incentives are more effective.

Still, more work needs to be done to develop ideas, frameworks, and methodologies that might deepen both academic debate and practical implementation. Further research could be carried out to address sustainability transitions at multiple levels and scales. To create a dynamic platform to track the effectiveness of urban transitions, in which more social indicators connected to public response and participation might be created, documented, and assessed to provide timely grassroots information. Nevertheless, sustainability challenges are different for cities with different resource endowments, local financial strength, development difficulties, and social and humanistic environments. The prominent contradiction and path dependency are distinctive. There is no uniform model applicable to all. Urban transition research must fit in regional specificity by linking complex sustainability challenges to adaptive governance. Moreover, transitions toward sustainability require continuous learning and adaptation. Research on sustainability transitions would still be challenging due to the expanding diversity and societal importance of this field. It could be beneficial to consider the ways in which intentional activities and greater social transitions are mutually reinforced.

Policy implications for urban transitions in industrial cities. Jinchang City is no exception facing problems that hinder urban transitions from "unsustainable" to "sustainable". The challenges have been framed in terms of conceptual and institutional constraints, economic development models, innovation and human capital deficiencies, governance failure, and public participation in both decision-making and daily performance. These challenges are representative of most industrial cities. As many previous studies have proven, our case study also found that it is not easy for resource-dependent cities to accomplish economic transformation just via market forces and fragmented company self-adjustment. Path-dependencies related to economic growth modes and governance paradigms might continue to hinder the disruptive transformation of resource-dependent cities. However, the city might use its advantages in specialty industries and creative environmental renovation initiatives to change its traditional development mode and build new sectors that support a sustainable image. This transformation is dependent on effective local adaptations and new tactics tailored to the local context. Managing the transitions toward sustainability is not a matter for the government alone, but governance is of great importance to deal with the complexities, conflicts, and interdependencies during this transitional process.

Our findings suggested that the sustainability transitions of industrial cities would be framed into resource sustainability and social sustainability. The former focuses on improving material use efficiency and sustaining economic growth, which could profit from its early preparation for changing existing industrial systems, adopting circular and cleaner techniques, and regrowing new industries. The latter needs to be rooted in deeper societal transformations to bring into effect the multifunctionality of cities, consider socio-human elements, and adopt inclusive and differentiated strategies and paths. Positive changes in the urban ecological environment and liveability could benefit from both above via mitigating negative environmental impacts. All these transformations do not happen alone, but across domains, in practice, they involve the coevolution of technological, social, and governance changes from a system's perspective (Frantzeskaki et al. 2021; Loorbach et al. 2017).

Transitions toward sustainability is not only proposing a strategy for change but involve the stages of collecting large amounts of data and information, learning, and identifying problems within the system, setting practical targets and approaches, interacting with multiple stakeholders with different interests, and evaluating and readjusting to new problems and objectives. Notably, sustainable transitions take account of various decisions made by multi-agents of governments, private sectors, and civil society, where the importance of individual behavioural change for social transformation is particularly integrated. The complexity of urban systems determines that the urban transitions may confront structural, technological, financing, and social constraints, and not all efforts would get the desired results or sometimes the negative rebound effects may exceed the expected benefit. Few successful initiatives and structural reforms may dramatically alter urban growth in the direction of sustainability (Khan et al. 2020; McCormick et al. 2013). Governance failure is often the result of a lack of knowledge and expertise, the need to incorporate environmental-based analysis and democratic involvement in integrated urban decision-making cannot be overstated (Maiello et al. 2013; Santos, 2017), while constant practices and experience learning are also indispensable.

Making the shift to sustainable urban development calls for a complex combination of policies and multilevel collaboration. There are several options for promoting urban transitions. Firstly, promoting enterprise vitalities and policy support in industrial transformation and diversification to meet both environmental and resource depletion challenges. Specific measures could be applicable through utilizing comparative advantages to reform the industrial and energy structure for optimizing the allocation of resources, reducing the proportion of mining industries to extend industrial chains and cultivate successive industries, and encouraging technological innovation and enterprise openness to generate pathways of industrial diversification for both resource-based and non-resource-based industries. Secondly, improving urban governance, particularly in government-led transition management maximizes the government's advantages in mobilizing resources and institutionalizing multi-level cooperation. In this process, policy orientation and framework at the national level are crucial for breaking down institutional barriers, particularly in GDP-based "yardstick competition", and establishing behavioural choices for officials. Local government should actively create favourable market, educational, and cultural environments for stimulating disruptive transformations. Through on-the-job training and personnel exchange within and outside the system, government employees could become transformational governors. Thirdly, promoting a greater level of public engagement and multistakeholder cooperation in decision-making to increase local strategic competency and exert authority over the direction and fundamental approaches to urban transitions. Fourthly, developing effective incentive programs and environmental infrastructure to encourage a broader social transformation. This contributes, but is not limited to changing values and beliefs, bridging the gaps between knowledge and practices, and establishing eco-friendly lifestyles. Finally, promoting human capital management, reaching out to external forces to break path dependency, and expanding cross-regional cooperation is critical for cities in underdeveloped regions. Local governments should create preferential policies and a humanistic environment to deal with these intellectual and technological deficits inherent in less developed regions.

Conclusion

Advancing urban sustainability transitions might be promoted by integrative transformations informed by a comprehensive understanding of urban systems connected to greater knowledge from both biophysical and social perspectives. Our study found the primary obstacles to sustainable transitions in industrial cities have been defined in terms of development model lock-in, conceptual and institutional limitations, innovation and human capital inadequacies, and governance failure. The strong dependence of Jinchang City on non-renewable resources drove the unsustainable trajectory of urban metabolism, but decoupling negative material outputs, increased material efficiency, and environmental regeneration all point to the possibility of sustainability transitions. The simultaneous progress of the economy and the environment requires the dematerialization process and disentanglement of economic growth from extensive material consumption. Our study also found that the commitment of stakeholders, institutional setting, and personal development create a strong societal base for urban transitions. Bridging the knowledge-practice gap is a major barrier to sustainable choices and behaviours in many spheres of production, management, and social life. To address the key challenges defined in this research, we suggested a system of integrative transformations that is government-led, multi-faceted, and environment-adaptive. These transformations encompass cross-level synthesis of institutional reform, technical innovation, economic transformation, environmental rehabilitation, social and behavioural changes, and intellectual capital management. In this transitional process, the competence of government officials and urban governance plays a critical role in overcoming the hindrances from the trade-offs and institutional limits, formulating locally appropriate industrial planning, and creating a favourable environment for economic, educational, and cultural development. Governments could be both the agents of planning and reform as well as the facilitators of creating conditions required for long-term transformation. This necessitates the government taking the lead and organizing multiple resources for urban transformations, while encouraging participatory and collaborative techniques to incorporate multiple stakeholders' innovative solutions to urban problems.

This study serves as an urban transition model for China's fast-industrializing cities. Successful urban sustainability transitions in fast-industrializing cities have far-reaching consequences for numerous cities. There is no standard template for all cities, but many common strategies and behaviours can be applied to most industrial cities and many other parts of the world with similar economic-societal-environmental considerations. It is suggested that a sustainable future can only be made possible by efforts that reflect the interconnected complexities of urban sustainability transition research that have been defined in this study.

Data availability

Available as supplementary material.

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Author contributions

Ying Li: Conceptualization, Methodology, Writing- original draft, Formal analysis, Resources; R.J.S. Beeton: Conceptualization, Writing- review & editing, Supervision; Xiaofeng Zhao: Supervision, Project administration; Yeting Fan: Software, Visualization; Qingke Yang: Resources, Formal analysis; Jianbao Li: Conceptualization, Proofreading; Linlin Ding: Resources, Proofreading.

Competing interests

The authors declare no competing interests.

Ethical approval

The ethical approval was obtained from the ethics officer in School of Geography, Planning, and Environmental Management of The University of Queensland [ethical approval number: GPEM 20130001]. All procedures adhered to the ethical conduct in research involving human participants set by The University of Queensland.

Informed consent

All participants were previously informed about the purpose of the study by providing an information sheet on University letterhead paper that includes specific items of information about the study. The sheet also incorporates a specified "Ethical Clearance" paragraph indicating that the study has received clearance from the ethics committee of The University of Queensland. Informed consent was obtained from each participant. They were informed that their personal details, including names, workplaces and positions, would be anonymized and their information would be used exclusively for research purposes. Research ethical principles were applied throughout the whole research to protect the anonymity, dignity, and rights of all participants.

Additional information

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Correspondence and requests for materials should be addressed to Ying Li or Xiaofeng Zhao.