ICDSST 2023 on Decision Support System in an Uncertain World: The Contribution of Digital Twins The Application of Digital Technologies in the Agri-Food Supply Chain of China: Enablers Identification and Prioritization

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ABSTRACT

Agri-food supply chains (AFSCs) are facing more pressures in terms of increasing volatility, growing population, and intensifying climate change. It is expected that global agri-food production must be doubled by 2050 in order to tackle the world population explosion crisis. Digital technologies have the capability to produce more food with fewer resources, reduce food waste and loss, and revolutionize the agri-food industry completely, which has been widely recognized by scholars and practitioners as a potential solution. However, it is not clear about enablers to facilitate digital technologies application from a developing country's perspective. Thus, this study aims to analyze enablers to the application of digital technologies in the AFSC of China. Three research questions were formulated to understand what digital technologies are applied in the China's agri-food industry, what are the enablers to facilitate AFSC practitioners to use digital technologies, and how the identified enablers are prioritized. To answer these research questions, we employed a mixed-method approach, including semi-structured interviews to collect empirical data from 16 experienced AFSC practitioners, thematic analysis to identify enablers, and fuzzy analytical hierarchy process (AHP) to prioritize the identified enablers.

Our study significantly contributes to new knowledge. For example, this study identifies that frequently discussed digital technologies such as blockchain technology, big data analytics, and automatic tractor are seldom used in the agri-food industry of China, other technologies such as water-fertilizer integrated technology, internet of things (IoTs), and smart greenhouses are widely deployed. Ten enablers are identified that may facilitate AFSC practitioners to apply digital technologies, including those merely mentioned by scholars, such as workforce reduction, early detection of plant diseases, accurate determination of the maturity of crops, and improving working conditions. Finally, our prioritization results show that reducing working intensity, reducing water and fertilizer consumption, and improving fertilizer use efficiency are the top three enablers. This study also contributes to managerial practices.

Keywords: Agri-food supply chain, Digital technologies, Fuzzy AHP, Enablers identification and prioritization

INTRODUCTION

Digital technologies are the digital tools, systems, devices and resources that generate, store or process data. Their advantages in speeding communication, facilitating interaction, strengthening data security, and accelerating automation have been widely recognized by researchers and practitioners [1]. Thus, various digital technologies such as IoTs, blockchain technology, robotics, machine learning (ML), and artificial intelligence (AI) are applied to improve products, services, and processes. For example, blockchain technology has been applied to improve AFSC's traceability performance by providing security and full transparency. IoTs have been applied to reduce incorrect deliveries, excessive waiting time, and product losses. Extant literature in this filed has analyzed barriers and enablers to the adoption of different digital technologies, the application of digital technologies in improving supply chain resilience, sustainability, and leanness, and the implications of digital technologies on supply chain management, a paucity of them has investigated enablers to the adoption of digital technologies of AFSCs from a developing country's perspective. In particular, China's agri-food industry is moving from Industry 1.5 to Industry 4.0 by employing different digital technologies, having an understanding on the enablers to the adoption of digital technologies would help practitioners and policymakers better deploy these technologies. Thus, this study aims to analyze enablers to the application of digital technologies in the AFSC of China. Three research questions are formulated:

RQ1: What digital technologies are applied in the AFSC of China?

RQ2: What are the enablers to facilitate AFSC practitioners to apply these digital technologies?

RQ3: How are these identified enablers prioritized?

To answer RQ1, we employed semi-structured interviews to collect data from experienced AFSC practitioners from China to understand what digital technologies have been applied in the AFSC. To answer RQ2, thematic analysis was adopted to identify enablers to the adoption of digital technologies. To answer RQ3, we adopted fuzzy AHP to understand the relative importance of the enablers to adopt digital technologies [2]. AHP is a widely applied multi-criteria decision-making (MCDM) method to prioritize alternatives based on pair-wise comparisons. However, the pair-wise comparison may be imprecise due to involvement of subjective judgements. Thus, fuzzy sets have been combined with AHP to alleviate the uncertainty of human judgements and improve accuracy of the present work.

The remainder of this paper is organized as follows. A review of relevant literature discussing enablers to the adoption of digital technologies in supply chains is presented in Section 2. The research methodology is discussed in Section 3, while the empirical data collection process is shown in Section 4. In Section 5, we presented the data analysis process and findings of this study. Finally, discussion and conclusions are presented in Section 6.

LITERATURE REVIEW

Agri-food production must be doubled by 2050 to fulfil the global population demand and the world's population is expected to increase significantly to 9.7 billion by 2050 [3]. A feasible way to achieve this task is to equip AFSCs with digital technologies to produce more food with fewer resources, reduce food waste and loss, and revolutionize the agri-food industry completely. Thus, various researchers have dedicated themselves into investigating digital technology application of agri-food industry. For example, [4] research results indicate that higher income for farmers, increased output, and improved food security are the top three enablers for African farmers to use digital tools. After analyzing enablers to use electronic traceability in Indian AFSC, [5] proposed that competitive advantage, coordination and transparency, management support, and appropriate technology for e-traceability are the significant enablers to e-traceability implementation. Exploring digital technologies application in agri-food industry is a trending topic. Various research areas are explored, including sustainability, business model and framework establishment, using digital technologies to tackle the COVID-19 crisis, and optimizing AFSCs with different digital technologies. However, a rare of them have analyzed enablers to the application of digital technologies in the AFSC of China, which pertains a valuable research gap that should be filled.

RESEARCH METHODOLOGY

A mixed-method approach was adopted in this study because of its advantages in balancing out the limitations of each method, strengthening findings, and providing a better understanding of the problem. Thus, three methods were adopted in this study, including semi-structured interviews, thematic analysis, and fuzzy AHP.

Semi-structured interviews were employed in this study to collect data from experienced AFSC practitioners. We selected this data collection method because it provides us with a set of themes to focus on and is less formal than structured interviews, thereby providing flexibility in exploring the perceptions and opinions of respondents.

Thematic analysis was then selected to identify, analyze, organize, describe, and report themes found within the data collected from semi-structured interviews. Thematic analysis was selected over content analysis, narrative analysis, and discourse analysis because it does not require the detailed theoretical and technological knowledge of other qualitative approaches, provides a more accessible form of analysis, and fewer prescriptions and procedures to implement it [6].

Finally, fuzzy AHP was implemented to prioritize the enablers identified by thematic analysis. Fuzzy AHP is widely applied in social, manufacturing, political, industry, and government areas because of its ease of use, structuring problem systematically, and calculating both criteria weights and alternative priorities.

EMPIRICAL DATA COLLECTION

We conducted empirical data collection activities in China between December, 2021 and April, 2022. We selected this specific time period to collect data because of different agricultural technologies (e.g., temperature, light, and humidity management systems) are frequently used during wintertime of China in order to provide sufficient off-season vegetables to Chinese. Thus, it would be easily for us to know what digital technologies have been used in the agri-food industry of China. China was selected to conduct research because of two reasons. First, we have wide connections with the agri-food industry of China because we participated in several projects funded by Horizon 2020 and National Natural Science Foundation of China. The collaboration allowed us to find suitable participants to participate in this research. Second, Chinese government proposed to achieve climate-smart agriculture in 2035 and began investment to facilitate agricultural science and technology innovation. Thus, we believe that more digital technologies should be applied to accelerate the transformation of China’s agri-food industry.

We developed an interview guide to enable participants to focus on the topic. The interview guide contains three sections, including interviewee information, main digital technologies applied in the agricultural sector, and enablers to apply digital technologies in the agricultural sector. Then, we conducted pilot interviews with two professors in operations and supply chain management and one agri-food industry practitioner. The pilot interviews suggest that more elaborations on the interview questions should be given. For example, more examples on digital technologies should be given when we are asking the question “what kind of smart technologies have been applied in the agricultural sector of China”.

Purposive sampling was applied to recruit suitable participants to participate in this research. Two criteria were applied: (1) the selected participants should be the technical lead or senior level members of their organization, to ensure they have sufficient understandings on smart or digital applications in agriculture, and (2) the selected participants should have more than 10 years working experience on the agri-food industry to ensure high-level professional experience and knowledge. Based on our criteria, 16 agri-food professionals were selected and were all happy to accept our interviews. Two co-authors of this paper who are affluent in Chinese and have interests in agri-tech acceleration conducted the interviews.

DATA ANALYSIS AND FINDINGS

In this section, we elaborated how the enablers were identified through thematic analysis and how the identified enablers were prioritized through fuzzy AHP.

Enablers identification through thematic analysis

The qualitative data collected through semi-structured interviews were analyzed through thematic analysis. The analysis approach consists of five steps: transcribing, familiarizing, coding, categorizing, and producing results. Initially, each interview audio file was transcribed verbatim to ensure that we understand any elements emerged from the responses given by the interview participants. Then, repeated reading of the transcripts several times until we are familiar with all aspects of our data. Thereafter, data relevant to enablers for applying digital technologies in AFSCs were coded inductively. During the open coding process, *NVivo* 13 was applied to assist the retrieval and management of data. Next, the codes derived from the open coding process were then collapsed into second-order themes, which were labelled using established constructs from the literature of digital acceleration in agri-food industry. We also synthesized a number of overarching themes that characterize the key concepts in the analysis. Finally, we produced a table that includes first-order codes, second-order themes, and overarching themes to present our findings. Based on our analysis, we identified ten enablers across human resource management (reducing work intensity, improving work conditions, and workforce reduction), crop management (early detection of plant diseases, accurate determine the maturity of crops, food safety improvement), and environment sustainability categories (reducing carbon emissions, reducing water and fertilizer consumption, improving fertilizer use efficiency, avoiding groundwater pollution).

Enablers prioritization through fuzzy AHP

The identified ten enablers were then prioritized through fuzzy AHP. The fuzzy AHP approach implemented in this study consists of five steps.

Step 1: Hierarchical structure construction. This step involves understanding the objective of this study. One of the research objectives is to rank the enablers of applying digital technologies in the AFSC of China. Thus, we constructed a three layers hierarchical structure to assist understanding, including the objective was placed on the top layer of the hierarchical structure followed by the evaluation criteria on the second layer, and then the enablers were placed on the bottom layer.

Step 2: Constructing the fuzzy judgment matrix $\tilde{E}$. The fuzzy judgment matrix $\tilde{E}$ is pairwise comparison among each enabler and evaluation criteria. Assign linguistic terms to the pairwise comparisons by asking which one of two criteria is more important:

$$\tilde{E} = \begin{bmatrix} \tilde{1} & \tilde{E}_{12} & \dots & \tilde{E}_{1n} \\ \tilde{E}_{21} & \tilde{1} & \dots & \tilde{E}_{2n} \\ \dots & \dots & \dots & \dots \\ \tilde{E}_{n1} & \tilde{E}_{n2} & \dots & \tilde{1} \end{bmatrix} = \begin{bmatrix} \tilde{1} & \tilde{E}_{12} & \dots & \tilde{E}_{1n} \\ \tilde{E}_{12}^{-1} & \tilde{1} & \dots & \tilde{E}_{2n} \\ \dots & \dots & \dots & \dots \\ \tilde{E}_{1n}^{-1} & \tilde{E}_{2n}^{-1} & \dots & \tilde{1} \end{bmatrix},$$

Where

$$\begin{cases} \tilde{1}, \tilde{3}, \tilde{5}, \tilde{7}, \tilde{9}, \text{criterion i is relative importance to criterion j,} \\ \tilde{1}, i = j, \\ \tilde{1}^{-1}, \tilde{3}^{-1}, \tilde{5}^{-1}, \tilde{7}^{-1}, \tilde{9}^{-1}, \text{criterion i is relative less importance to criterion j} \end{cases}$$

Step 3: Calculating fuzzy weights of each criterion. The fuzzy weights of each criterion are calculated based on the research of [6]. Details are shown as follows:

$$\tilde{r}_i = [\tilde{E}_{i1} \otimes \tilde{E}_{i2} \otimes \tilde{E}_{13} \dots \otimes \tilde{E}_{in}]^{1/n}, \forall \text{i} = 1, 2, 3\dots, \text{n},$$

$$\widetilde{w}_i = \frac{\tilde{r}_i}{\tilde{r}_1 \oplus \tilde{r}_2 \oplus \tilde{r}_3 \dots \oplus \tilde{r}_n},$$

where $\tilde{E}_{ij}$ is the fuzzy comparison value of criterion i to criterion j, $\tilde{r}_i$ is the geometric mean of fuzzy comparison value of criterion i to each criterion, and $\widetilde{w}_i$ is the fuzzy weight of the ith criterion.

Step 4: Hierarchical layer sequencing. The final fuzzy weight value of each alternative is calculated by hierarchical sequencing as

$$\widetilde{U}_i = \sum_{j=1}^{n} \widetilde{w}_j . \tilde{r}_{ij}$$

where $\tilde{r}_{ij}$ is the fuzzy weight value of the jth criterion to the ith enablers. $\tilde{u}_i$ can be indicated by a triangular fuzzy number, $\widetilde{U}_i = (l, m, u)$.

Step 5: Ranking enablers. The final fuzzy weight values of enablers are represented in terms of fuzzy numbers. Thus, we follow the method proposed by [8] to defuzzify and rank the fuzzy numbers.

$$x(\widetilde{U}_i) = (l + m + u)/3$$

Based on the value generated by the above equation, we can rank and determine the optimum enablers. The data analysis results are shown in Table 1. For example, human resource management holds the first rank, environmental sustainability comes second, and crop management occupies the third place in the priority list. Among the identified ten enablers, reducing work intensity ranks first, followed by reducing water and fertilizer consumption and improving fertilizer use efficiency hold the second and third places in the priority list. It is easily to understand that managers using digital technologies in AFSCs is to reduce operational costs.

Table 1 Final ranking of enablers to digital technologies adoption

Category of enablers	**Relative weighting**	**Relative rank**	**Specific enablers**	**Relative weighting**	**Relative rank**	**Global weighting**	**Global rank**
Human resource management	0.7125	1	Reducing work intensity	0.7125	1	0.2864	1
			Improving work conditions	0.0675	3	0.0303	9
			Workforce reduction	0.2200	2	0.0775	5
Environmental sustainability	0.2180	2	Reducing carbon emissions	0.1108	3	0.1124	4
			Reducing water and fertilizer consumption	0.6139	1	0.2173	2
			Improving fertilizer use efficiency	0.2301	2	0.1342	3
			Avoiding groundwater pollution	0.0451	4	0.0305	8
Crop management	0.0695	3	Early detection of plant diseases	0.6069	1	0.0314	7
			Accurate determine the maturity of crops	0.0872	3	0.0160	10
			Food safety improvement	0.3058	2	0.0639	6

DISCUSSION AND CONCLUSIONS

This study employs a mixed-method approach to analyze enablers to the apply of digital technologies in the AFSC of China. Three RQs were formulated in this study, including RQ1: what digital technologies are applied in the AFSC of China, RQ2: what are the enablers to facilitate AFSC practitioners to apply these technologies, and RQ3: how are these identified enablers prioritized. In answering RQ1, we employed semi-structured interviews to collect data from 16 experienced AFSC practitioners. This study identifies that water-fertilizer integrated technology, IoTs, and smart greenhouses are frequently used by the AFSC practitioners, whereas other technologies such as blockchain technology, big data, and automatic tractor are seldom used because of various barriers. In answering RQ2, thematic analysis was used to analyze the data collected from the semi-structured interviews. Based on the thematic analysis results, we identified 10 enablers that may facilitate AFSC practitioners to apply digital technologies, such as workforce reduction, reduce water and fertilizer consumption, and early detection of plant diseases. In answering RQ3, fuzzy AHP approach was employed to rank the identified enablers. Among all categories of enablers, the human resource management category receives the highest priority weight, whereas crop management category holds the last place in priority list. Among the identified ten enablers, the top three enablers are reducing work intensity, reducing water and fertilizer consumption, and improving fertilizer use efficiency. Currently, one and a half tons of agrichemical products and approximately 500 kilograms water are used in cultivating one acre of vegetable in China in comparison with only one third are used in developed countries. The application of digital technologies has great potential in helping Chinese farmers to reduce water and fertilizer consumption, further helping to achieve environmental sustainability.

This study does have limitations. For example, this study concentrates only on the farming stage of AFSCs, not including other stages such as food processing, wholesaling, distributing, and marketing. This is the reason why the identified digital technologies such as water-fertilizer integrated technology and smart greenhouses, are only related to farming. Further study could extend this work by interviewing processors, wholesalers, logistics service providers, and retailers to get a more comprehensive understanding on digital technology application in the AFSCs.

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