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Towards Sustainable Agriculture 4.0: Reducing Fluoride Stress in Crops through Ecological Intensification Practices

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ABSTRACT

Background: Sustainable Agriculture 4.0 is centred on the convergence of modern technologies with ecological intensification techniques as the means of dealing with such environmental issues as fluoride pollution in soils and on crops. Adverse health effects of excessive stress fluoride are lower agricultural productivity and poor crop quality, jeopardizing food security in areas with naturally-occurring fluoride. Although the above prospects hold the potential of Agriculture 4.0 very well, little is known concerning the impact of fluoride-related measures of adopted technology and task and technology fit (TTF) on outcomes of sustainable farming.

Objective: This paper examines how fluoride-management task requirements, facets of technology, and management prerequisite influence task technology fit and consequently their impact on real-life technology utilization and performance outcomes with regard to fluoride stress.

Methods: A questionnaire-based survey was carried out in 500 Chinese farmers in fluoride-enriched agricultural regions providing 378 valid responses after data correction. A Partial Least Squares Structural Equation Modeling (PLS-SEM) was used to assess the measurement and structural models.

Results: The findings reveal that the task requirement of fluoride-management, in terms of technology factors, and management capacity are the strong discerning factors of task-technology fit. Task-technology fit, in its turn, contributes greatly to real use of technologies and decreases the negative effects of fluoride stress on the performance. Indirect effects were confirmed by mediation analyses across constructs.

Conclusion: The present study enhances TTF theory in the agricultural dimension and presents empirical support in developing fluoride-centered interventions within the globalized framework of Sustainable Agriculture 4.0.

Keywords: *Sustainable Agriculture 4.0; Fluoride stress; Task–Technology Fit; Technology adoption; Crop performance*

INTRODUCTION

Sustainable agriculture has become widely accepted as a necessity in the increasingly stressed environmental conditions, animal farmers struggle to maintain in providing food security as the world population grows. Fluoride toxicity in soils is one of such stresses that has gained prominence but remained unexploited (Li et al., 2025). In most farming areas, high concentrations of fluoride are due to industrial presence, water pollution, and use of phosphate-based fertilizers over a long period of time. Over-dosage of fluoride alters physiology of plants by inhibiting

photosynthesis, uptake and absorption of nutrients, as well as root growth resulting in stunted growth and low yields. Convention methods of alleviating fluoride stress have long rested on chemical amendments and remediation practices, the former of which alone are regularly quite expensive, environmentally burdensome, and ineffective in situations that require a degree of site responsiveness (Sharma, 2025). In this context, the synergy between Agriculture 4.0 technologies and ecological intensification measures provides a new solution that will better deal with fluoride stress more sustainability, adaptively and data-driven.

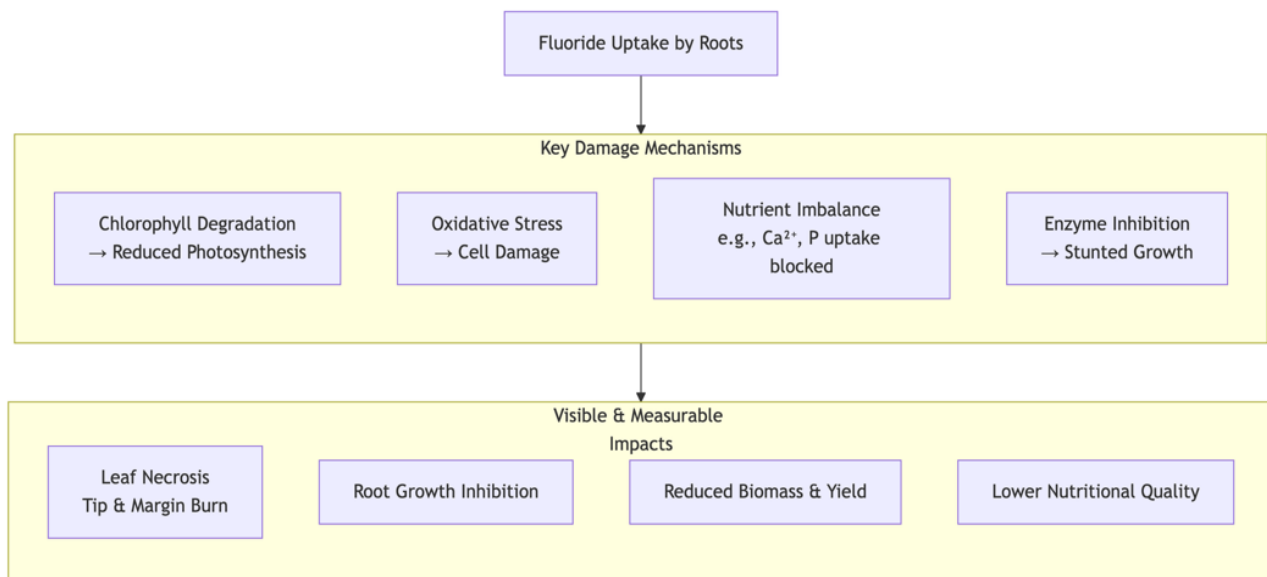


Figure 1: Fluoride ions disrupt crucial plant processes (Self-generated)

Note: The biochemical level, which manifests as visible stress symptoms and ultimately leads to significant reductions in crop yield and quality, threatening food security.

The figure 1 below shows the cascade of physiological disturbances that occur when fluoride is taken up into plants which starts at the root level and is observed visibly as plant stress symptoms. After absorption, fluoride disrupts a number of important metabolic pathways. It also increases the rate of chlorophyll breakdown, which lowers levels of photosynthetic performance, thus restricting energy production. At the same time, oxidative stress destroys the cellular components, and the affected metabolism retains nutrients rarely absorbed (namely, calcium and phosphorus). Moreover, fluoride prevents the action of enzymes and this leads to general suppression in growth. Combined, these internal processes have quantifiable crop level effects. Farmers can see noticeable signs which may include leaf-necrosis (tip and margin burns), poor root extension, a decrease in biomass, and yield loss (Li et al., 2025). In addition, the nutritive value of crops produced is compromised, which puts food security and marketability at risk. This mechanistic chain of events under stress due to fluoride (uptake to the impacts) clearly indicates why fluoride stress is a major challenge in sustainable agriculture and should be addressed through a combination of mitigation strategies.

Agriculture 4.0 includes a range of digital, automated, sensor-based technologies, that allow farmers to track the condition of the soil and plants in real-time and make a specific management decision. Ecological intensification, on the other hand, focuses on such practices as crop diversification, organic amendments and soil health management out to utilize ecological processes to boost crop resilience. Combined with Ag 4.0 and ecology intensification, tools

can identify and disrupt the contamination before it causes any damage, intervention that decreases the bioavailability can be made easier and finally natural defense system of plants can be reinforced (Raj et al., 2021). As another example, fluoride sensors paired with decision support tools can be used to time and calculate soil amendment dosage, and ecologically-friendly soil amendments like the addition of organic materials and intercropping can mitigate plant stress. The effectiveness of these integrated strategies however does not only depend on their technical soundness but also on how in sync such an approach is with the fluoride-management work farmers have to accomplish, and how capable or willing they will be to adopt such strategies.

Fluoride toxicity in the soils has become one of these stresses that have received little attention. Fluoride concentration is high in most areas where agriculture is practiced due to the influence of industry, and groundwater pollution and long-term phosphate fertilizers. The issue of the deposition of fluoride in farm soils has become a developing international problem that threatens the crop growth, absorption of nutrients, and stability of crop yields, recent studies have indicated that this is a severe problem in the agricultural heartland of China (Li et al., 2019; Sawyer et al., 2024). The surplus fluoride interferes with the physiological activities of plants by affecting their photosynthesis, uptake of nutrients and root growth to stifle growth and produce low yields.

Although such innovations hold a lot of promise, little empirical evidence is available on their suitability in managing fluoride stress. The large body of literature regarding precision agriculture and digital farming

addresses generic aspects of yield maximization or overall resource productivity but does not entertain a critical examination of real-life applied abiotic stress, such as fluoride toxicity. This presents a vulnerability: technologies might be available, but it remains unclear whether the characteristics of these technologies, e.g. accuracy of fluoride sensors or reliability of decision support, are truly in line with the task requirements of fluoride management (Rashid & Gani, 2025). Moreover, different farmers possess varying agronomic skills, digital maturity, as well as resources, and this casts doubt on their ability to transfer the technological inputs into positive performance specialists. The problem is thus not only technological but the ability to establish good task-technology fit which overcomes the gap between tools, tasks and farmer capacities.

The Task-Technology Fit (TTF) model provides a sound basis upon which to discuss this overlap. By noting how the technology attributes, job tasks and personal attributes collaborate to produce fit, the model notes the circumstances in which technology adoption will result in superior performance and veritable use. In this fluoride stress context, this model enables the researcher to inquire further about whether Agri 4.0 tools in conjunction with ecological intensification indeed meet the specific challenges of fluoride management and whether the farmers feel and experience any performance advantages (Minhas & Obi Reddy, 2017). In this framing, characteristics of technology involve the features of sensors and decision systems to detect fluoride; task requirements are related to the multi-faceted actions necessary to decrease the stress caused by fluoride; individual abilities are related to skills that farmers have in both agronomy and digital tools; and task technology fit serves as a mediator between these antecedents and subsequent performance advantages and actual use.

In this way, the research problem can be described as follows: the potential of Agriculture 4.0 technologies and the application of ecological intensification practices potentially capable of mitigating the fluoride stress in crops has not been studied widely yet, and little is known about the alignment of these technologies with the tasks of fluoride management and the skills of farmers, which is a prerequisite to the effective adoption of these technologies (Minhas & Obi Reddy, 2017). This leaves doubt on the role that Ag 4.0-based ecological intensification can play in sustainable agriculture under conditions of fluoride stress.

Based on this issue, the research question developed becomes: What are the degrees to which technology characteristics, task requirements, and farmer capabilities shape a task-technology fit in fluoride stress control and how does such fit in turn affect performance outcomes and actual adoption of Ag 4.0-enabled low-carbon intensification technologies?

The current research should help to examine the significance of task-technology fit to mitigate stress in crops caused by elemental fluoride administration with the usage of Agriculture 4.0 technologies and ecological intensification. Using the TTF model, the researchers will attempt to assess the way the congruence of technologies, tasks, and farmer abilities leads to the achievement of sustainable performance and actual adoption. In the process of doing so, the study helps the field at a theoretical level by putting the TTF approach to new use, in the area of fluoride stress, which has limited research; and practically by providing data that policymakers and the forces of technology can use to contribute to the development of sustainable Agriculture 4.0.

LITERATURE REVIEW

Task Technology Fit Model

The agriculture sector is experiencing a super-charge revolution as a result of the adoption of the concept of Agriculture 4.0 whereby, digital tools are deployed in the agricultural sector using technologies like sensors, drones, data analysis and decision support. Extensive literature has shown success of the precision farming tools in terms of optimal utilization of inputs, minimizing production stipends, and enhancing production (Ahmad et al., 2025). Meanwhile, ecological intensification has been identified as a sustainably satisfying direction in agriculture that achieves this through the process of intensifying natural functions through organic additions, intercropping, application of conservation tillage (Mambile et al., 2025). Ecological intensification and Ag 4.0 promise to help with site-specific stress, such as fluoride toxicity plaguing soil fertility and crop health in the areas of industrial emissions, groundwater contaminants, or fertilizer byproducts.

Fluoride stress has also been found to inhibit photosynthesis, alter nutrient uptake, and lower plant productivity (Mishra et al., 2024). Conventional cleanup treatments- like chemical correction or phytoremediation- can be costly and have limited application and applicability. New developments in sensor technology now allow soil and plant fluoride levels to be measured, and decision support systems can advise on steps taken at an ecological level, such as the use of organic matter to allow the fluoride to be bound or creating new crop diversity to increase resilience. But the success of these technologies varies beyond their availability to their ability to match the targeted priorities of fluoride management work and the capacity of farmers to settle these tools in their proper use.

An information systems theory perspective known as the Task-Technology Fit (TTF) model can be used to shed more light on this alignment. According to the

model, benefit in technology use results when the set of technology attributes, task demands and user skills are such that the entire set achieves a high level of task-technology fit. The features of technology used in the agricultural environment can be precision and confidence of fluoride sensors, and usability of decision support platforms (Castiblanco Jimenez et al., 2021). The Task requirements include monitoring of fluoride level in the soil, irrigation and fertilization regime changes, and ecological practices that will alleviate the stress of fluoride. Personal skills such as digital literacy of farmers, Agronomic knowledge, and previous experience with smart farming tools. A combination of all these three antecedents lead to a greater perceived fit between the technology and the tasks to be undertaken by the farmers.

In this context, task-technology fit (F-TTF) plays a seminal mediating role and affects both F-PERF and use (F-AU) of Ag 4.0-enabled ecological intensification. The high fit is supposed to enhance yields stability, crop damages caused by fluoride, and sustains adoption. Specifically, by directly integrating fluoride stress into the TTF model, the given study lays out a new research direction that would target an understudied environmental stress factor and apply a model to test it.

HYPOTHESES DEVELOPMENT

Technology Characteristics and Task–Technology Fit

Technology characteristics are specified as functional features and qualities of a system which determines its capability to enable users in their work. Some of them relate to the accuracy, effectiveness, and conveniences of tools like soil and leaf sensors, drone-based monitoring, and decision support systems, in the context of Agriculture 4.0. Applied to fluoride stress management, F-TECH would include the sensitivity of sensors to detect soil and plant fluoride levels correctly, the ultimate timeliness and dependability of results presented to the farmer via the decision support system, and the ease at which farmers read the data streamed into it via their computer interfaces.

TaskTechnology Fit (TTF) theory states that the correlation between the capabilities of a technology and the demands of a specific task will lead to the user experiencing a greater level of fit (Castiblanco Jimenez et al., 2021). To illustrate, as long as an actionable recommendation is provided by a decision support system perfectly matching the requirements of managing fluoride toxicity, the related task–technology fit level will be higher among the farmers. Such technology that is too complex, unreliable or has irrelevant outputs, on the other hand, will be seen to have low fit. In previous studies on precision agriculture, it has also been established that synchronicity in technological features and agricultural requirements

augers well in terms of likelihood of the technological utilization and better performance (Nordin et al., 2022).

Hypothesis 1: *Fluoride-related technology characteristics (F-TECH) have a positive effect on fluoride task–technology fit (F-TTF).*

Task Requirements and Task–Technology Fit

Task requirements are the specific actions, decisions and processes that have to be accomplished to get the desired objectives. Among these requirements in fluoride stress management are soil/plant-fluoride monitoring, imparting ecologically friendly practices like addition of organic matter in situ to bind fluoride, and set of irrigation/fertilization timing to minimize the effect of stress. Task requirements (F-TASK) can thus be used to describe the amount and the intricacy of work required in the process of remedying fluoride toxicity.

The TTF model suggests that the level of fit will rise when the use of technology is aligned directly with complexity and priorities of the task (Patil & Pramod, 2022). In case farmers also regard fluoride management as a serious and hard assignment, and they feel that Ag 4.0 technologies can assist them (e.g., by reliably identifying fluoride levels, by promptly providing warnings, issuing useful suggestions), then they will have a superior perceived task-technology fit. Empirical works on farming contexts indicate that technologies that fit particular and high-priority farming tasks are more inclined to be taken on and interwoven into practice (Sachitra & Wimalasena, 2024).

Hypothesis 2: *Fluoride-management task requirements (F-TASK) have a positive effect on fluoride task–technology fit (F-TTF).*

Individual Abilities and Task–Technology Fit

F-ability includes individual abilities or skills, knowledge and resources which farmers bring to use of technology. The digital literacy, agronomic knowledge regarding the soil to plant interactions and prior knowledge to sustainable farming practices applied to the sustainable greek farms are the abilities that have been considered in this research. Farmers with good skills can easily decipher fluoride-related sensor information, implement ecological intensification practice, change management approaches guided by technology advice.

The TTF framework points out that user competence is determinant of how the level of accessing technology towards tasks achievement can be accomplished, (Sachitra & Wimalasena, 2024). Even sophisticated technologies cannot succeed in bringing on their gains without the input of the user who has to be qualified to handle the output and interpret the same. On the other hand, with high levels of ability underlying users, they can fully exploit the utility of technology by ensuring its compatibility with requirements of particular tasks. Studies going back

more than a decade have reliably shown that perceived fit and subsequent adoption of precision farming tools is positively correlated to farmer capabilities.

Hypothesis 3: *Fluoride-management abilities (F-ABILITY) have a positive effect on fluoride task–technology fit (F-TTF).*

Task–Technology Fit as a Mediator

The most vital step in the ttf model is the assertion that technology characteristics along with task level demands and ability of users affect the results in a roundabout manner through task technology fit. Fit is the linkages between antecedent conditions and performance benefits and sustained use (Huynh-Xuan et al., 2024). Technology characteristics may be irrelevant, requirements of the task may not be addressed, and individual capabilities may not be taken up without a great sense of fit. The schematic structure of this study consists of fluoride task - technology fit (f-ttf) mediating relationships between three antecedents, namely: fluoride technology-task (f-tech), fluoride task (f-task), and fluoride ability (f-ability) on the two targeted outcome variables; performance impact (f-perf) and actual use (F-AU).

Mediation of F-Tech and Outcomes

Most probably, the effect of high-quality technology characteristics like precise sensors and dependable decision support is not to be direct: accurate sensors and dependable decision support is only one of the conditions of efficient fluoride management. Such features will only benefit farmers when they have a perception that the technology fits the tasks they perform in relation to fluoride management. This fit perception translates unprepared technological capabilities into operational solution (Nguyen et al., 2024). Coming up with high fit levels, farmers become more willing to achieve performance improvements, including stable yields and the minimization of fluoride-related damages, as well as to adopt the chosen tools on a regular basis. High-quality technology characteristics may not be utilized at optimum level without such fit.

Hypothesis 1a: *Fluoride task–technology fit (F-TTF) mediates the relationship between fluoride-related technology characteristics (F-TECH) and fluoride-related performance impact (F-PERF).*

Hypothesis 1b: *Fluoride task–technology fit (F-TTF) mediates the relationship between fluoride-related technology characteristics (F-TECH) and fluoride-related actual use (F-AU).*

Mediation of F-Task and Outcomes

The role of task requirements has the same effect as on task outcomes; the task requirements affect the outcome through task-technology fit. Farmers may see fluoride management as one of the important complex

tasks, but unless they are convinced that technology meets those needs algorithms, there will be no improvement in performance and adoption. Task-technology fit thus mediates the significance of tasks by converting that value into usefulness. Once farmers feel that the tools can offer meaningful assistance in terms of fluoride monitoring, soil management and interventions in ecology, the fit is enhanced, which results in more benefits in terms of performance as well as actual utilization of the tools.

Hypothesis 2a: *Fluoride task–technology fit (F-TTF) mediates the relationship between fluoride-management task requirements (F-TASK) and fluoride-related performance impact (F-PERF).*

Hypothesis 2b: *Fluoride task–technology fit (F-TTF) mediates the relationship between fluoride-management task requirements (F-TASK) and fluoride-related actual use (F-AU).*

Mediation of F-Ability and Outcomes

Last but not least the relationship between individual abilities and outcomes is supposed to be mediated by task technology fit. Farmers with high digital literacy level and potent agronomic understanding are in a better position to match the needs of the technology with their management procedures. Such competence allows them to have a perception of high fit, thus resulting in better performance and frequent use. Equally, the absence of the sense of fit may not enable even able farmers to turn their skills to sustained gains. The mediating function of fit guarantees that the capacity of the farmers is directed towards considerable adoption and performance improvement.

Hypothesis 3a: *Fluoride task–technology fit (F-TTF) mediates the relationship between fluoride-management abilities (F-ABILITY) and fluoride-related performance impact (F-PERF).*

Hypothesis 3b: *Fluoride task–technology fit (F-TTF) mediates the relationship between fluoride-management abilities (F-ABILITY) and fluoride-related actual use (F-AU).*

METHODOLOGY

Research Design

The research was conducted on a cross-sectional survey design where the proposed tasktechnology fit (ttf) model regarding agriculture 4.0 and ecological intensification practice of fluoride stress management can be empirically tested. The design was selected so as to permit the gathering of standardized data on a large sample of respondents and to permit complex structural relationships to be tested involving several latent variables and mediating effects.

Study Area

The study was initially done empirically in the areas in china that are fertile as well as those which have elevated fluoride levels in the soils and groundwater. He chose henan province, especially luoyang and anyang counties both as one of the grain-producing regions of china, and due to documented fluoride contamination associated with fertilizer residues and industries. The second site of investigation based on intensive wheat and maize production and frequent occurrences of the exceedences of the safe value of groundwater fluoride levels was chosen in the jinan plain of the shandong province. A third location was identified in baotou, inner mongolia, geogenic factors

in this area result in very high soil and groundwater fluoride; the area is nonetheless intensively cultivated in cereals and vegetables. Collectively, these locations offered a sampling ground to analyze fluoride stress encountered in chinese agriculture.

Instrument Development

The TTF literature was searched and a structured questionnaire on the same was designed to be used to collect data based on TTF specific literature on fluoride stress management. The operationalization of each construct was as a reflective latent variable on a five-point likert scale (1 strongly disagree, 5 strongly agree). The detailed measurement item for survey instrument is presented in table 1 below.

Table 1. Measurement Items for Survey Instrument

Construct	Code	Survey Item
Fluoride-Related Technology Characteristics (F-TECH)	F-TECH1	The system provides accurate data on fluoride levels in my soil.
	F-TECH2	The sensors reliably monitor crop exposure to fluoride stress.
	F-TECH3	The decision support system gives useful recommendations for fluoride management.
	F-TECH4	The interfaces of the tools are easy to use and interpret.
	F-TECH5	Overall, the technology is reliable for reducing risks from fluoride stress.
Fluoride-Management Task Requirements (F-TASK)	F-TA SK1	Monitoring soil fluoride levels is an essential task on my farm.
	F-TASK2	Adjusting irrigation and fertilization is critical to reduce fluoride stress.
	F-TASK3	Timely interventions are necessary to protect crops from fluoride damage.
Fluoride-Management Abilities (FMA)	FMA1	I am skilled in using digital tools (e.g., sensors, apps) to monitor fluoride stress.
	FMA2	I have enough agronomic knowledge to manage fluoride-related crop issues.
	FMA3	I can effectively apply ecological practices (e.g., organic matter, intercropping) to reduce fluoride stress.
Fluoride Task–Technology Fit (F-TTF)	F-TTF1	The technology fits well with the requirements of managing fluoride stress.
	F-TTF2	The system provides functions that I need for fluoride stress management.
	F-TTF3	The tools match the way I manage crops under fluoride conditions.
	F-TTF4	Overall, the technology is a good fit for fluoride stress management.
Fluoride-Stress Performance Impact (F-SPI)	F-SPI1	Using Agriculture 4.0 tools improves my crop yields under fluoride stress.
	F-SPI2	These practices reduce visible crop damage caused by fluoride.
	F-SPI3	This approach enhances the efficiency of managing fluoride stress.
Fluoride-Focused Actual Use (FFAU)	FFAU1	I frequently use sensors to monitor fluoride levels in my fields.
	FFAU2	I apply ecological intensification practices (e.g., organic fertilizers, intercropping) based on fluoride data.
	FFAU3	I rely on decision support systems for fluoride stress management.
	FFAU4	I regularly adjust my farming operations using Ag 4.0 fluoride insights.
	FFAU5	I consistently integrate fluoride management tools into my farming routine.

Fluoride-Related Technology Characteristics (F-TECH): Five items investigating precision, reliability and usability of Ag 4.0 sensors as well as decision support systems to monitor and negate fluoride.

Fluoride-Management Task Requirements (F-TASK): There are three items that reflect complexity and the significance of a task related to fluoride stress reduction, such as monitoring the soil fluoride and modifying irrigation or fertilization.

Fluoride-Management Abilities (FMA): Three items assessing farmers digital literacy, agronomic knowledge and their ability to implement ecological intensification practices.

Fluoride Task-Technology Fit (F-TTF) four items assessing the extent of misalignment between fluoride-management activities, Ag 4.0 tools, and ecological practices.

Fluoride-Stress Performance Impact (F-SPI): Three questions in regards to the outcomes like yield stableness, fluoride damage inhibition, and the efficiency increase.

Fluoride-Specific Real Use (FFAU): Five questions based on the frequency and regularity of implementing Ag 4.0 tools and ecological intensification practices by fluoride-stressed management.

The questionnaire was first written in English then, a back translation technique that entails the use of the same concept was employed in order to achieve conceptual equivalence in Mandarin. A pilot test of 30 farmers in Henan Province was done to make modifications on the wording of items and to ensure clarity. Cronbach alpha values exceeded 0.70 in all the constructs in the reliability tests conducted as part of the pilot, indicating that the internal consistency is acceptable.

Data Collection

The survey carried out in the field was done at the peak of the crop growing season that spans between May and September in the year 2024 due to the greatest visibility of fluoride stress in agricultural activities. Laboratory-trained, Mandarin- and local-dialect fluent enumerators captured face-to-face interviews involving farmers in the field or in their homes. Respondents could base their answers on demonstrations of Ag 4.0 devices provided by enumerators (Mazhar et al., 2021). These included soil fluoride sensors and mobile-based decision support systems to help them minimize the comprehension barriers. The technique avoided the use of force and demanded that all the respondents gave their consent freely and the practice of strict confidentiality and anonymity was kept to. The study was given ethics clearance by institutional review board of the host university.

Population and Sampling

The intended population consisted of smallholder and medium-scale farmers who participated in crop cultivation in the region with high levels of fluoride. The criteria that respondents needed to fulfill in order to be relevant consisted of the following three discrete conditions: (i) the cultivation of at least one hectare of land, (ii) implementation of a ecologically-friendly escalation such as the use of organic fertilizers, intercropping, or crop rotation, (iii) familiarity with logistics to some degree of exposure to tools of Agriculture 4.0 like sensors, decision-support systems, or mobile advisory platforms.

A multi-stage enumeration was used. Provincial districts found to have enriched concentration of fluoride were selected purposively. Within these districts, villages were selected at random. Lastly, systematic sampling of farmers was conducted by use of village rosters. In sum, 450 questionnaires were deployed in the three regions of study (150 each). Of the 450 questionnaires sent out, 392 filled questionnaires were yielded after discarding incomplete ones hence effective response rate of 87.1 percent.

Demographic Grouping of the Respondents

The demography of the respondents has been summarized in Table 2. It shows that there were many men farmers, but women participated too which is representative of agricultural household gender distribution. Majority of the respondents were captured within the 36-50 years and with substantial proportion over 50 years, indicating the participation of older farmers in making decisions about agriculture. The level of education was mixed with most respondents being high school graduates but not enough could be found with only a primary school certificate. The size of farms was skewed toward the small side (under 2 hectares), and 45.2 percent of individuals in the study sample had more than 15 years of farming experience indicating experienced farmers.

Table 2: Demographic Characteristics of Respondents (N = 392)

Variable	Category	Frequency	Percentage (%)
Gender	Male	238	60.7
	Female	154	39.3
Age	Below 35 years	84	21.4
	36–50 years	176	44.9
	Above 50 years	132	33.7
Education Level	Primary or below	136	34.7
	Secondary	162	41.3
	Post-secondary & above	94	24
Farm Size	Less than 2 hectares	214	54.6
	2–5 hectares	127	32.4
	Above 5 hectares	51	13
Farming Experience	Less than 10 years	86	21.9
	10–15 years	124	31.6
	Above 15 years	182	46.5

DATA ANALYSIS

With SmartPLS 4, partial least squares structural equation modeling (PLS-SEM) was employed to do the data analysis. This procedure was chosen because it is appropriate to diverse models for estimating a multiple latent variable, reflective measures and mediating variables. To analyze this, the analysis was done in a two-step procedure. The measurement model was tested to ensure indicator reliability, construct reliability, convergent validity and discriminant validity. Second, structural model was evaluated to test the hypothesized relationships. Path coefficients were estimated, and their significance is determined by bootstrapping owing to 5,000 subsamples. Indirect effects were tested, and bias-corrected confidence intervals were estimated. Control variables included size of the farm, lifetime experience in farming, and nature of crops farmed were included to explain the heterogeneity in the nature of the farmers.

MEASUREMENT MODEL

First assessment of the measurement model was done to determine the psychometric parameters of the constructs. As stated in Table 3, the standardized (FL) factor loadings were well over the advised cut-off of 0.70 (Hair et al., 2019) of 0.863-0.980. These findings are consistent in indicating that every indicator had a high interrelation with its target latent variable. Some

of example inputs include that the F-TECH loaded between 0.947 and 0.974, the F-TASK element registered between 0.977 and 0.980. On the other hand, fluoride-management talent (FMA) items had a loading range of between 0.863 and 0.926, fluoride-task-technology fit(F-TTF) items 0.898 and 0.963, fluoride-stress performance effect (F-SPI) between 0.917 and 0.954, and fluoride-focused genuine use (FFAU) between 0.915 and 0.943. All these findings indicate good reliability of the indicators of all the constructs (Fornell & Larcker, 1981).

Internal consistency was also ratified The Cronbach alpha (CA) values are within the acceptable range of 0.70 and above as estimated by Table 3 (0.882-FMA to 0.980-F-TASK). The composite reliability (CR) values were between 0.927 and 0.985, and again, they confirm internal consistency and construct reliability. The convergent validity was considered using average variance extracted (AVE). All the constructs had AVE values above the cut-off point of 0.50 with the lowest being 0.809 (FMA) and the highest 0.957 (F-TASK), indicating that the individual indicators explained a great part of the variance of the underlying construct corresponding to them.

Table 3: Factor Loading's of the Constructs

Constructs	Items	FL	CA	CR	AVE
Fluoride-Stress Performance Impact	F-SPI1	0.954	0.929	0.955	0.876
	F-SPI2	0.917			
	F-SPI3	0.937			
Fluoride-Management Task Requirements	F-TASK1	0.980	0.977	0.985	0.957
	F-TASK2	0.977			
	F-TASK3	0.977			
Fluoride-Related Technology Characteristics	F-TECH 1	0.966	0.980	0.984	0.927
	F-TECH2	0.974			
	F-TECH3	0.947			
	F-TECH4	0.964			
	F-TECH5	0.962			
Fluoride Task–Technology Fit	F-TTF1	0.963	0.944	0.960	0.857
	F-TTF2	0.932			
	F-TTF3	0.898			
	F-TTF4	0.909			
Fluoride-Focused Actual Use	FFAU1	0.928	0.962	0.970	0.867
	FFAU2	0.943			
	FFAU3	0.915			
	FFAU4	0.925			
	FFAU5	0.943			
Fluoride-Management Ability	FMA1	0.926	0.882	0.927	0.809
	FMA2	0.909			
	FMA3	0.863			

Discriminant validity was then tested by using the heterotrait monotrait (HTMT) ratio. The Heterotrait-Monotrait ratio (HTMT) measures the discriminant validity between the fluoride-related constructs, namely, Fluoride Task-technology Fit (F-TTF), Fluoride-Focused Actual Use (FFAU), Fluoride-Management Ability (FMA), Fluoride-Management Task Requirements (F-TASK), Fluoride-Related Technology

Characteristics (F-TECH), and Fluoride-Stress Performance Impact (F-SPI). Values of HTT measure the proximity in the similarity of constructs; the value below the conservative 0.85 or liberal 0.90 level suggests satisfactory discriminant validity. In this table the least significant correlations are between 0.237 and 0.625, which is far inferior to the level of 0.85. The highest interrelation can be seen to exist between FMA and F-TTF (0.625), that is, management ability and fit, which is conceptually closest, whereas the lowest relationship is evident between F-TECH and F-SPI (0.237), which are highly distinct. In general, it is clear that these constructs are empirically different, which minimizes any issues of multicollinearity and can offer strengthened reliability when performing further structural analysis. Therefore, the validity of the measurement model indicates the presence of a sufficient discriminant validity. All HTMT values are less than the conservative limit of 0.85 with values, being in

the range of 0.237 - 0.625. The lowest figure was recorded between F-TECH and F-SPI (0.237), which shows that the two constructs have minimal common variance and are therefore highly differentiated (Hair et al., 2019). The Fornell-Larcker criterion has also supported discriminant validity as indicated in the results. Based on this requirement, the square root of each AVE must be higher than the correlations of the given construct with other constructs. The results affirm this assumption of all the variables in the study. To illustrate, AVE square root of F-TTF was 0.926, which was higher than its correlation with FFAU (0.560) and F-SPI (0.491). This shows that the variance handled by F-TTF was more than that common with other constructs. Correspondingly, F-TECH reported a square root of AVE of 0.963 that surpassed its best correlation to other construct, namely, F-TTF (0.481). Discriminant validity was also demonstrated even with cons The Fornell-Larcker criterion has also supported discriminant validity. Based on this requirement, the square root of each AVE must be higher than the correlations of the given construct with other constructs. The results affirm this assumption of all the variables in the study. To illustrate, AVE square root of F-TTF was 0.926, which was higher than its correlation with FFAU (0.560) and F-SPI (0.491). This shows that the variance handled by F-TTF was more than that common with other constructs.

Correspondingly, F-TECH reported a square root of AVE of 0.963 that surpassed its best correlation to other construct, namely, F-TTF (0.481). Discriminant validity was also demonstrated even with constructs with high correlations with product values, such as FMA and FFAU ($r = 0.540$), where the square roots of AVE of individual constructs (0.900 and 0.931 for FMA and FFAU respectively) were substantially large.

The combination of the results in (HTMT), and (FornellLarcker) gives strong indication that the constructs in the study are unique and not overlapping. This is essential in confirming the effectiveness of the Task-Technology Fit (TTF) model in the particular case of the Agriculture 4.0 and fluoride stress applications as it confirms that the idea of technology characteristics, tasks requirements, farmer abilities, and tasks-technology fit are conceptually distinct although they might be interconnected.

STRUCTURAL MODEL

Following the reliability and validity of the measurement model, the hypothesis relationships between the constructs of the model were to be tested. Analysis was performed through partial least squares structural equation modelling (PLS-SEM), and presented as shown in Table 4. The table gives the original sample estimates, the sample mean, standard deviation, t-statistic and p-value of each hypothesized path. Collectively these findings form a judgment of both direct and indirect outcomes in the determination of the implementation and success of Agriculture 4.0 practices in lessening fluoride stress.

Direct Effects

The results affirm that fluoride task-technology fit (F-TTF) has an immense impact on inducing influence on fluoride-targeted certain use (FFAU) and fluoride-

stress performance-influence (F-SPI). The path coefficient of F-TTF to FFAU was 0.560 with a t-value of 26.553 and a p-value of 0.000 implying highly significant and positive impact. This shows that the more farmers feel comfortable that the technology suits their activities of controlling fluoride that they engage in during the farming practice, the greater the possibility of adopting and applying the technology in the farming practices. Similarly, the one between F-TTF and F-SPI was also noteworthy ($\beta = 0.491$, $t = 21.875$, $p = 0.000$), indicating that optimized technology-task match had a positive effect on the overall performance results in countermeasuring fluoride stress, including higher yields of crops, less crop injuries, and greater efficiency in managing them.

All three antecedents to task-technology fit fluoride-management ability (FMA), fluoride-management task requirements (F-TASK), and fluoride-related technology characteristics (F-TECH) had a significant, positive influence on F-TTF. In particular, F-TECH had 0.284 ($t = 12.244$, $p = 0.000$), F-TASK had the highest coefficient of influence 0.307 ($t = 12.149$, $p = 0.000$), and FMA had 0.298 ($t = 10.186$, $p = 0.000$). These findings clearly show that both task requirement, characteristics of the technology and the capacities of the farmers themselves exert relatively equal influence in the perceptions of fitness. This would imply that adoption of agricultural 4.0 tools by the farmers is not only dependent on the technology itself, but also on the tasks they are carried out and skills the farmers have.

Mediation Effects

The mediating role of F-TTF was tested against all three antecedents with reference to both FFAU and F-SPI. As demonstrated in Table 4, it was confirmed that there were significant indirect effects that are significant in all paths, thus confirming mediation.

Table 4: Path Coefficients of the Study

Relationships	Beta	Mean	SD	T-Value	P values
F-TTF -> F-FAU	0.560	0.560	0.021	26.553	0.000
F-TTF -> F-SPI	0.491	0.491	0.022	21.875	0.000
FMA -> F-TTF	0.298	0.298	0.029	10.186	0.000
F-TASK -> F-TTF	0.307	0.307	0.025	12.149	0.000
F_TECH -> F-TTF	0.284	0.284	0.023	12.244	0.000
FMA -> F-TTF -> FFAU	0.167	0.167	0.019	8.994	0.000
F-TASK -> F-TTF -> FFAU	0.172	0.172	0.016	10.599	0.000
F-TECH -> F-TTF-> FFAU	0.159	0.159	0.014	11.373	0.000
FMA -> F-TTF-> F-SPI	0.147	0.147	0.017	8.823	0.000
F-TASK -> F-TTF -> F-SPI	0.151	0.151	0.015	10.226	0.000
F-TECH -> F-TTF -> F-SPI	0.139	0.140	0.013	10.759	0.000

First, FMA had a very strong effect on FFAU through F-TTF ($\beta = 0.167$, $t = 8.994$, $p = 0.000$). This indicates that the technical ability and knowhow of the farmers on managing stress of the presence of fluoride does not directly correlate to their technological use. Rather their capabilities improve adoption when they feel that the technology is suitable to meet their tasks. The same pattern was identified in performance impact where FMA indirectly affected F-SPI through F-TTF ($\beta = 0.147$, $t = 8.823$, $p = 0.000$). In such a manner, farmer capabilities enhance crop resistance to fluoride stress only when they are perfectly matched to the functions of technology.

Second, F-TASK had a substantial indirect impact on FFAU ($\beta = 0.172$, $t = 10.599$, $p = 0.000$) and F-SPI ($\beta = 0.151$, $t = 10.226$, $p = 0.000$) through (F-TTF). These results indicate that the task design (e.g., soil fluoride level monitoring or irrigation and fertilizers adjusting) is not a sufficient condition for increasing usage or better performance on their own. Rather, it is imperative that technology be seen to tie-in with such vital tasks. When there is a good fit of tasks and technology, farmers have greater likelihoods to incorporate the tools in practice and experience significant performance improvements.

Third, there were also substantial effects of F-TECH on both the outcomes through F-TTF. The beta on the indirect path to FFAU was 0.159 ($t = 11.373$, $p = 0.000$), whereas that on F-SPI was 0.139 ($t = 10.759$, $p = 0.000$). Such findings indicate that in order to know the full value behind powerful technological characteristics (e.g., sensitivity of fluoride sensors, quality of decision support systems), it is necessary to first ensure that the farmers can see value that they perceive to fit their needs in alleviating fluoride stress.

The general implication of mediation outcomes is the fact that F-TTF acts as a mediator through which antecedents affect adoption, as well as performance outcomes. This concurs with the theoretical postulations of the TaskTechnology Fit model that argues that the effects of technology are conditional to its fit with tasks and its users capabilities.

The results of the structural model support the conclusion that a combination of task, technology, and individual components is critical in fostering sustainable Agriculture 4.0 perspectives of fluoride-stressed environments. This important direct impact of F-TTF on both FFAU and F-SPI indicates that fit is the most effective promotion of enrolment and performance. At the same time, the substantial indirect effects demonstrate that the abilities of the farmers, technological characteristics, and task requirements only affect the results through their effects on perceptions of fit.

These observations are both theoretical and practical. Theoretically, the results confirm the TTF

model in the extension of ambience of ecological intensification and fluoride stress management to the venue of agricultural sustainability study. In practice, these results imply that policymakers, agricultural technology developers, and extension services should not concentrate the improvements of only the technological features. Rather, the instruments should be customized to the purposes and skills of farmers. As an example, the fluoride monitoring systems must be developed in such a way that they are easy to operate, and given the fact that farmers already have certain skills, the extension services should offer some training that will increase their capacity to integrate ecology when using technology.

Finally, structural model findings support the mediator theoretical orientation of F-TTF, which affects further adoption and consequent performance predispositions. The orientation of the characteristics of the technology, the needs of the tasks, and the skills of the users allows farmers to get as much out of Agriculture 4.0 tools as possible, as well as the minimum of benefits in terms of minimizing the impact of fluoride stress.

The structural model found that fluoride-management task requirements, technology characteristics, and farmer abilities significantly enhanced task technical fit (F-TTF), which positively and strongly influenced both use (actual) ($\beta = 0.560$, $p < 0.001$) and fluoride-stress performance impact ($\beta = 0.491$, $p < 0.001$). Mediation tests also showed that these antecedents had a mediated impact on adoption and performance via the perception of fit, justifying the fundamental position of F-TTF on endurable technology use.

To corroborate the foregoing findings, the strategy distribution analysis (Figure 2) illustrates how the strategy of Agriculture 4.0 and ecological intensification can be implemented to make crops stress free. The greatest share (25%) goes to precision agriculture tools because they result in the direct strengthening of the technology in the context of task alignment. Water and soil management practices (20%) indicate that it was necessary to implement task-oriented interventions that alleviated fluoride accumulation at its source. Crop diversification and rotation (20%) reflects ecological intensification as a way to increase resilience and make the long term adaptation to management activities. Organic amendments - these augment the model finding, with organic amendments described by 15 % of the farmers who answered the question, essentially reinforcing the mediated pathways in the model. Lastly, farmer knowledge and education (20%) point to the importance of management skills (FMA) as adoption and performance will only be realized when farmers are skilled and ready.

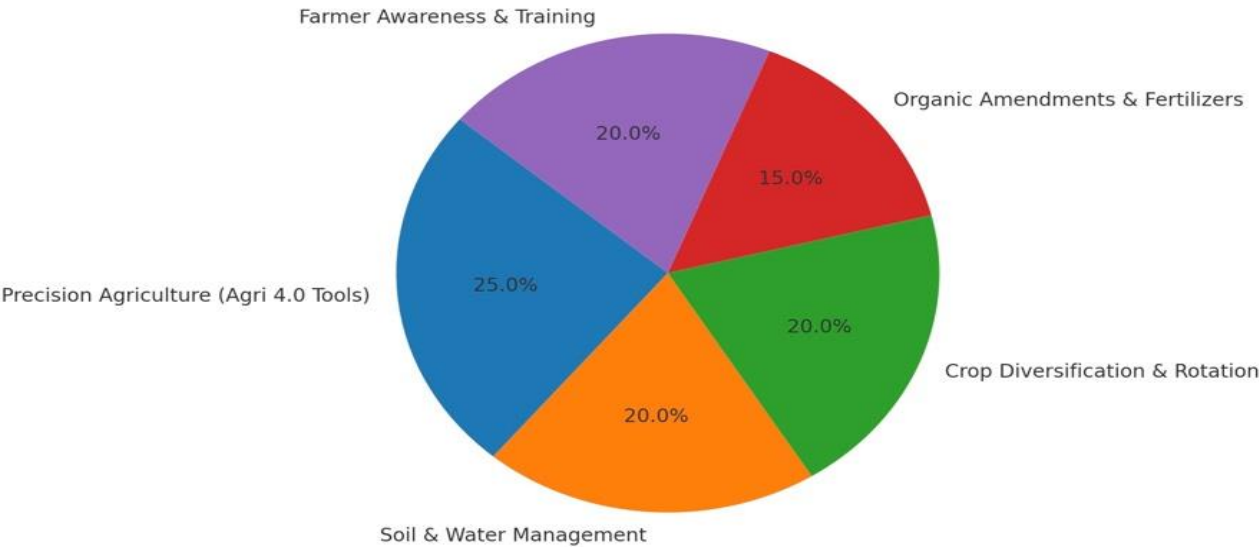


Figure 2: Strategic distribution analysis of Crops

A combination of the model outcomes and pie chart planning demonstrates that effective technologies are not the only requirement to have sustainable management of fluoride, a demand-driven practice and capacity building is also needed. Such a combination of different approaches will mean that Agriculture 4.0, and ecological intensification will complement each other in reducing the stressing factor of fluoride as well as increasing crop productivity.

DISCUSSION

The current research tested how task-technology fit (TTF) can promote Agriculture 4.0 practices to address fluoride stress in crops. Through structural equation modeling, the results supported all three pathways of fluoride-management abilities, fluoride-management task requirements, and fluoride-related technology characteristics positively affecting perceptions of task-technology fit, which positively impact both fluoride-focused actual use and fluoride-stress performance outcomes (Choudhary et al., 2019). This evidence illuminates the interaction between technology, duties, and the capacities of farmers that define the sustainable agricultural practices in the conditions of environmental stress.

Among the key contributions of this research, it validates the fact that task-technology fit is critical in the process of Agriculture 4.0 adoption (Alam et al., 2025). The large path coefficients, both actual use and performance outcomes indicators, symbolize that the technological adoption in farming cannot merely be based on availability or access but on the compatibility of what the technology can provide and farmers require in terms of day to day activities (Huang, Chen, et al., 2025). This is similar to previous results in

information systems study where TTF was found to be a key factor in the utilization and effectiveness of systems. In the agricultural setting, this implies that even well-designed fluoride-monitoring systems or decision support tools can be rendered largely ineffective unless and until farmers find themselves seeing these tools directly as a means of assisting them in their crop management regimen.

Specifically, the research emphasizes that the main Agriculture 4.0 technologies that include soil fluoride and moisture sensors, remote sensors with used drones, GIS and GPS-based irrigation systems, as well as decision-support systems relying on real-time data can significantly influence task-technology fit development (Garg et al., 2024). To illustrate, fluoride sensors can be installed on the soil, giving the farmers real-time data on the level of fluoride in the root zone, thus enabling them to modify irrigation practices accordingly. In a similar fashion, mapping of crop stress symptoms associated with fluoride hotspots through drone-based imaging can be used to produce a high-resolution map which can be the basis of an ecological intervention. These instruments offer practical information about the chemistry of soil, places of accumulation of fluoride, and timing of irrigation and hence these tools are much aligned with the daily chores of farmers in regard to fluoride management (Patel et al., 2024). Indirectly by stating how these precision technologies directly decrease uncertainty, enhance the accuracy of monitoring and allow targeted ecological interventions, the findings support the practical importance of TTF as a sustainable agricultural technology in fluoride stress.

The findings indicate that farmer skills are critical in conditioning the perceptions of fitness. Farmers who were more knowledgeable and skilled at coping with

fluoride stress had in turn a more positive perception of highway light technology as being commensurate with their activities, which influenced greater adoption and improved performance (Huang, Gao, et al., 2025). This points to the relevance of capacity building in the process of agricultural technology diffusion. Good designs of technologies can be rendered useless by the competencies and skills of end-users. Such an observation echoes the insights made by ecological intensification scholars, which hold that sustainable agricultural methods need not only new instruments but also the experiences and input within the farmers.

Task requirements also came out as a powerful determinant of TTF, suggesting the need to acknowledge the real circumstance of farm-level fluoride control (Malik et al., 2024). It is necessary that the monitoring of the soil, effects on the irrigation regimes, and practicing ecologically correct production in the form of organic fertilizers, interplanting should be timely, and accurate information. Technologies that best serve these requirements are seen as more valuable and as such, easier to adopt (Luo et al., 2024). This observation supports the contention that technology in agricultural practice should be demand-driven, where farmers needs and issues should be considered primarily to determine the future development of tools and technologies.

The characteristics of technology were also identified as the factor that pushed teams forward in terms of TTF, but the impact of this factor was a bit weaker in comparison to task requirements. This implies that features, like accuracy, reliability and usability are very necessary but not a sure way to good adoption or improving performance. Rather, their influence comes through the perception of fit. This is in line with the precision agriculture literature that has shown farmers do not adopt digital technologies because of the technological sophistication but rather because they find them either useful or easy to integrate into their farming activities (Rose & Chilvers, 2018). The findings of the mediation increase the confidence that TTF is the primary mechanism that the antecedents influence adoption and performance. The task requirements, farmer skills, and technology characteristics did not have a direct influence on on-the-job use and performance results. Rather, the influence of these factors was entirely through task-technology fit. This is in line with the fundamental idea of the TTF model that states that technology effectiveness is subject to alignment with tasks and users. Within the framework of fluoride stress control, this suggests that not only do farmer skills, the value of fluoride-related jobs, and the characteristics of technologies bear relevance, but their value is limited to their effects on perceived fit. Collectively, these results contribute to the knowledge on sustainable Agriculture 4.0, introducing the concept of ecological intensification and environmental stress management

to the TTF scheme (Feng et al., 2025). This has helped emphasize the importance of precision technologies and ecological farming in tailoring the technological solutions and methodological approaches to agricultural challenges which can be in this case fluoride stress which has been underreported in terms of influencing technology adoption in agricultural activities. The findings support the notion that adoption and performance are not the singular processes but interdependent processes that are influenced by the congruence between various dimensions.

IMPLICATIONS

Theoretical Implications

This research offers contributions to theory in a number of ways. First it is an expansion of the TaskTechnology Fit (TTF) model to the context of sustainable agriculture, i.e., it discusses a specific phenomenon that has not been considered previously in the scope of the TTF model (namely, fluoride stress). Although TTF framework has found much usage in information systems and management research, its utilization in the research on agricultural sustainability has not been fully exploited. By using it in this context, the research shows the strength of the concept scaling within other domains as well and identifies the significance of the concept of fit as an intermediary mechanism in technology adoption.

Second, the study is more precise in its explanations of the contribution of antecedents like the capabilities of farmers, needs of tasks and the technology features on the results. Instead of directly influencing our results, these antecedents do act through task-technology fit, which has been theorized to mediate the task-technology fit relationship. This observation provides depth to other studies because it elucidates how adoption and performance improvements are attained in agrarian environments.

Third, this incorporates the ecological intensification strategies and environmental stress control into the TTF framework, which is also new. The study contributes to theoretical frameworks of agricultural sustainability, demonstrating how technological and ecological aspects interrelate to realise resilience when the reduction of fluoride stress and the pursuit of Agriculture 4.0 are linked.

Practical Implications

The paper also gives practicable information to practitioners and policymakers. Agricultural technology developers need to lay greater emphasis on designing tools that offer direct response to the task requirement of the farmers. To illustrate, decision support systems and fluoride-monitoring sensors should help draw such actionable information that may be linked to specific

farming processes, e.g., irrigation management and soil treatment.

Second, there should be improvement in training and extension services to empower farmers. With higher knowledge and skills, farmers feel more positively regarding task-technology fit and this leads to increased adoption and output. The delivered extension programs must thus entail both technology training and ecological information to create stability in how farmers adopt the climate-friendly practices in synergy with technology adoption.

Third, the policymakers are urged to develop favorable conditions of the adoption of Agriculture 4.0. Subsidies and investment in monitoring technologies that are fluoride-safe, investment in rural digital infrastructure, and policies that facilitate ecological intensification may all be used to make a more widespread adoption a reality. Notably, the policies ought to be localised in areas with above-average fluoride levels in water and soil, where the effects of their implementation will be noted.

Lastly, the findings underline the need to have a cooperation between technology developers, farmers, and agricultural extension officers. In co-design, the direct bargaining of the needs and capacities of farmers onto the process of tool development, the identified and realised fit can be expected to be stronger and lead to better adoption rates.

LIMITATIONS AND FUTURE RECOMMENDATIONS

Although this research has offered valuable insights, there are a number of limitations that have to be mentioned. First, some of the analysis will be based on self-reported scales of technology adoption that might not necessarily reflect behaviors or practices of farmers as they are and might also provide bias in response. Additionally, the results are derived using a specific set of data of a particular regional context and this restricts the generalizability of the results to a wider range of agricultural systems, crop types and regions that might experience varying types of environmental stress than those present in fluoride contamination. Furthermore, the cross-sectional research design limits the possibility of making long-term causal associations of task technology fit, adoption and performance outcomes. Further studies that would use longitudinal designs and a multi-country comparative study would offer more robust evidence and increase the generalizability of the findings across countries. Second, the study used cross-sectional design that limits causal conclusion. Longitudinal studies would be of greater strength, in ensuring how view of fit and adoption behaviours change over the years with the experience of the farmers with the new technologies. Third, the emphasis upon fluoride stress is limited. Further research might also add to the model

other environmental stresses (salinity, heavy metals, or climatic variability) to make it more useful in terms of agricultural sustainability.

Lastly, although this study concentrated in task-technology fit it would be appropriate in a future study to include other elements as social influence, support by the institution or economic rewards to develop a more comprehensive picture of adoption processes.

CONCLUSION

This study investigated how task-technology fit can encourage sustainable Agriculture 4.0 practices to mitigate fluoride stress in crops. The findings established the significant influence of farmer skills, work requirements and properties of technology in creating a feeling of fit that subsequently positively and negatively impact the actual use of technology and performance growth in relation to coping with the fluoride stress. As it is important to note, the mediating role of task-technology fit communicates that only perceived good task and technology fit will lead to adoption and performance advantages. The research is also a contribution made to the theory as it relates to the TTF framework on the agricultural sustainability by incorporating ecological intensification practices. In real terms, it explains why there must be a demand driven technology design, farmer training and conducive policies to facilitate adoption. As it is based on geography and scale restrictions, the evidence still constitutes a well-grounded contribution to future studies on the digital agriculture ecology direction and green stresses.

Finally, sustainable Agriculture 4.0 in fluoride-affected areas can be achieved only by more than just a powerful tool that is better suited to a farmer and his/her capacity. Upon this synchronization, there is a possibility to maximize the use of ecological intensification that can lessen the extent of fluoride stress and magnify crop outputs.

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REFERENCES

- [1]. Ahmad, M. S., Ahmad, M. N., Muhammad, T., Khan, M. J., Jabbir, F., Alghamdi, S. A., Alhomrani, M., Alamri, A. S., & Shah, S. (2025). Utilizing agricultural waste in brick manufacturing for sustainable consumption and circular economy. *Scientific Reports*, 15(1), 22741.

- [2]. Alam, M. A., Pal, S., Pal, S., Dutta, A., & Mandal, M. (2025). Impacts of Industrial Effluents on Plants and Their Effects on the Food Chain. In *Plant-Microbe Interaction under Xenobiotic Exposure* (pp. 197-242). Springer.
- [3]. Castiblanco Jimenez, I. A., Cepeda García, L. C., Marcolin, F., Violante, M. G., & Vezzetti, E. (2021). Validation of a TAM Extension in Agriculture: Exploring the Determinants of Acceptance of an e-Learning Platform. *Applied Sciences*, 11(10), 4672.
- [4]. Choudhary, S., Rani, M., Devika, O. S., Patra, A., Singh, R. K., & Prasad, S. K. (2019). Impact of fluoride on agriculture: A review on its sources, toxicity in plants and mitigation strategies. *Int J Chem Stud*, 7(2), 1675-1680.
- [5]. Feng, B., Gan, L., Men, Q., Liu, J., He, Y., Guo, N., He, T., Wang, X., Li, R., & Han, Y. (2025). Multivariate model for predicting crop fluorine content based on soil physicochemical properties and fluorine speciation. *Environmental Monitoring and Assessment*, 197(8), 863.
- [6]. Fornell, C., & Larcker, D. F. (1981). Evaluating structural equation models with unobservable variables and measurement error. *Journal of marketing research*, 18(1), 39-50.
- [7]. Garg, S., Rumjit, N. P., & Roy, S. (2024). Smart agriculture and nanotechnology: Technology, challenges, and new perspective. *Advanced Agrochem*, 3(2), 115-125.
- [8]. Hair, J. F., Risher, J. J., Sarstedt, M., & Ringle, C. M. (2019). When to use and how to report the results of PLS-SEM. *European business review*, 31(1), 2-24.
- [9]. Huang, X., Chen, K., Wang, C., & Gao, P. (2025). Characteristics of fluoride adsorption in different soil types: Potential factors and implications for environmental risk assessment. *Environmental Pollution*, 367, 125537.
- [10]. Huang, X., Gao, H., Chen, K., Wang, C., & Gao, P. (2025). Land-use change from wheat fields to kiwifruit orchards increases fluoride accumulation and associated environmental risks. *Journal of Hazardous Materials*, 139520.
- [11]. Huynh-Xuan, T., Bui, N., Ngo-Thanh, T., Nguyen, D. T., Thi Binh, A. D., & Le Thi Cam, H. (2024). Adopting construction 4.0 to promote sustainability in the Mekong Delta of Vietnam: a fuzzy delphi study. *Journal of Industrial and Production Engineering*, 41(4), 380-396.
- [12]. Li, D., Ning, S., Yu, L., Jiang, F., Zhao, D., Zhang, S., Liao, M., Meng, Q., Fang, Q., & Kang, H. (2025). Molecular Reconstruction for the High-Performance Recycled Fluororubbers. *Advanced Materials*, 2501622.
- [13]. Li, Y., Wang, S., Nan, Z., Zang, F., Sun, H., Zhang, Q., Huang, W., & Bao, L. (2019). Accumulation, fractionation and health risk assessment of fluoride and heavy metals in soil-crop systems in northwest China. *Science of the Total Environment*, 663, 307-314.
- [14]. Luo, H.-J., Pan, J., Chen, X.-X., Zhang, M., Shen, L.-C., Li, X., Ding, P., Cai, D., Cai, L.-M., & Hu, G.-C. (2024). Potential ecological risk characteristics and source apportionment of heavy metals in farmland soils around typical factories in Hunan Province based on Monte-Carlo simulation. *Huan Jing ke Xue= Huanjing Kexue*, 45(2), 1038-1048.
- [15]. Malik, A., Yasar, A., Tabinda, A., Iftikhar, M., & Mukhtar, S. (2024). Health risk assessment of nitrates and fluorides ingestion and geochemical evaluation of groundwater characteristics in semi-arid regions. *International Journal of Environmental Science and Technology*, 21(13), 8459-8486.
- [16]. Mambile, C., Mwangakala, H. A., Chali, F., Julius, B., Shao, D., Mongi, H., & Ishengoma, F. (2025). Evaluating Blockchain Technology for Contract Farming in Tanzania: A Task-Technology Fit Analysis. *Sustainable Futures*, 100905.
- [17]. Mazhar, S. A., Anjum, R., Anwar, A. I., & Khan, A. A. (2021). Methods of data collection: A fundamental tool of research. *Journal of Integrated Community Health*, 10(1), 6-10.
- [18]. Minhas, P., & Obi Reddy, G. (2017). Edaphic stresses and agricultural sustainability: an Indian perspective. *Agricultural Research*, 6(1), 8-21.
- [19]. Mishra, N., Bhandari, N., Maraseni, T., Devkota, N., Khanal, G., Bhusal, B., Basyal, D. K., Paudel, U. R., & Danuwar, R. K. (2024). Technology in farming: Unleashing farmers' behavioral intention for the adoption of agriculture 5.0. *PLoS one*, 19(8), e0308883.
- [20]. Nguyen, L. L. H., Khuu, D. T., Halibas, A., & Nguyen, T. Q. (2024). Factors that influence the intention of smallholder rice farmers to adopt cleaner production practices: An empirical study of precision agriculture adoption. *Evaluation Review*, 48(4), 692-735.
- [21]. Nordin, N. N., Nordin, N. H., Nordin, N. I. A., Mat Zaib, S. Z., Mohd Yasin, N. H., Nordin, N. F., & Abdullah, F. A. (2022). Adoption of Technologies and Innovations for Sustainable Rice-Paddy Farming in Kelantan. International Conference on Entrepreneurship, Business and Technology,
- [22]. Patel, T. K., Vasundhara, S., Rajesha, S., Priyalakshmi, B., Chinnusamy, S., & Boopathi, S. (2024). Leveraging drone and GPS technologies for precision agriculture: pest management perspective. In *Revolutionizing pest management for sustainable agriculture* (pp. 285-308). IGI Global.
- [23]. Patil, K., & Pramod, D. (2022). Examining the intention to adopt blockchain in the banking industry by combining task-technology-fit and technology acceptance theory. 2022 ASU International Conference in Emerging Technologies for Sustainability and Intelligent Systems (ICETSIS),
- [24]. Raj, A., Jhariya, M. K., Khan, N., Banerjee, A., & Meena, R. S. (2021). Ecological intensification for sustainable development. In *Ecological intensification of natural resources for sustainable agriculture* (pp. 137-170). Springer.
- [25]. Rashid, M., & Gani, G. (2025). Reimagining the Future of Sustainable Agriculture in South Asia: Integrating Ecological Resilience, Technological Innovation, and Inclusive Policy Reform for Transformative Agri-Systems. *Precision Agriculture and Climate-Resilient Farming: Artificial Intelligence, IoT, and Blockchain for Sustainable Agriculture*, 118.
- [26]. Sachitra, V., & Wimalasena, T. (2024). Employee acceptance of human resource management information system: Integrated UTAUT and TTF model in a selected public firm in Sri Lanka. *South Asian Journal of Social Studies and Economics*, 21(2), 75-87.
- [27]. Sawyer, W. E., Aigberua, A. O., Nwodo, M. U., & Akram, M. (2024). Overview of Air Pollutants and Their One Health Effects. In *Air Pollutants in the Context of One Health: Fundamentals, Sources, and Impacts* (pp. 3-30). Springer.
- [28]. Sharma, K. (2025). Eco-Friendly Approaches for Stress Resilience in Cereals: Current Status and Future Prospects. *Integrated Land and Water Resource Management for Sustainable Agriculture Volume 1*, 215-223.