

Article

Cross-Classification of Digital Tools and Learning Contexts for Safety Education and Training in Agriculture

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Abstract

Agriculture is one of the most hazardous occupational sectors, with conventional safety training often suffering from limited realism, low engagement, and reduced opportunities to reproduce hazardous scenarios safely. This article provides a structured analysis of digital and technology-enhanced approaches for safety education and training in agriculture. A literature-based framework was developed by combining five groups of digital tools—immersive technologies, simulators and digital twins, serious games and gamification, e-learning systems, and AI-based educational tools—with five learning contexts: formal education, vocational education and training, apprenticeships and traineeships, lifelong and on-the-job learning, and peer or community-based learning. In addition, a heuristic Application Priority Score (APS) was proposed to assess each technology–context combination according to evidence availability, cost–benefit feasibility, technology–learner fit, and inclusivity/accessibility. The results show that evidence is unevenly distributed, with stronger attention to immersive technologies, simulation-based approaches, and game-based learning in formal education, whereas lifelong, on-the-job, and peer/community learning remain less explored. The scoring framework also indicates that no single digital tool is universally suitable: the most promising solutions depend on the training context, learner experience, implementation costs, and accessibility barriers. The study provides a context-sensitive framework to support future research and the design of more inclusive and effective digital safety training solutions in agriculture.

Keywords: agriculture; training; safety

1. Introduction

Agriculture is often identified as one of the most hazardous occupational sectors, where fatal risks are three times higher than in other sectors [1] and non-fatal injuries and harmful exposures related to machinery, pesticides, animals, awkward postures, noise, dust, and extreme environmental conditions remain constantly present. Agricultural work, in fact, combines physical demands, environmental variability [2], and frequent interaction with potentially dangerous equipment. Given these conditions, safety strongly relies on effective education and training; however, conventional approaches are often constrained by low realism, reduced engagement, and limited opportunities to reproduce hazardous scenarios safely and repeatedly [3,4]. These limitations are particularly relevant in agriculture, where many risks are context-specific and strongly linked to practical experience. Agricultural safety education may address both task-oriented and hazard-oriented topics together with organizational or relational issues. The first group includes machinery operation,



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rollover prevention, chemical exposure, animal handling, ergonomics, and environmental hazards, while the second includes safety leadership, safety culture, communication, conflict management, and the challenges associated with multicultural and multilingual workforces. In this context, agricultural education is undergoing a broader digital transition for both the aforementioned groups. In a scoping review of educational technology in agricultural education [5], it was found that online and distance education technologies were the most widely represented category, followed by simulation and digital games, highlighting the growing role of technology-enhanced learning in agricultural training environments. Their review also pointed out that the literature remains methodologically heterogeneous and that important research gaps persist regarding the educational impact of these tools in agriculture. Within this technological evolution, immersive and interactive tools have attracted increasing attention in safety training research. In a systematic review of virtual reality for safety-relevant training [6], it was also shown that the use of this approach has grown rapidly and that most studies report positive effects, especially in terms of learner reaction and learning outcomes. Similarly, Scorgie [7] concluded that virtual reality-based safety training generally performs better than traditional training for knowledge acquisition and retention, supporting the educational value of immersive learning environments in hazardous domains. On the other hand, it should be mentioned that many different digital approaches are also relevant; reviewing digital games for occupational safety training, Vigoroso [8,9] noted that serious games and gamification have been applied successfully in several sectors but remain only marginally explored in agriculture despite their potential to improve engagement and safety awareness. In addition, AI-supported educational systems are becoming increasingly visible in training protocols; Labadze [10] showed that chatbots can support learners through immediate feedback, explanations, and personalized assistance, helping the educators through time-saving and pedagogical support. In parallel, recent reviews on digital twins in agriculture suggest that these systems can support simulation, monitoring, and scenario analysis, providing further possibilities for training environments based on realistic and data-informed representations of agricultural systems [11]. These existing studies have approached digital safety training from separate technological or educational perspectives, examining educational technologies in agricultural education broadly, immersive training in safety-critical sectors, digital games for occupational safety, and AI-supported learning or digital twins as individual technological domains, demonstrating the potential of specific tools but without comparing them within a common set of agricultural learning contexts. As a result, it remains difficult to determine whether the same technology is equally appropriate for formal education, vocational training, workplace learning, or informal community-based settings. Despite this growing body of literature, evidence remains unevenly distributed across technological domains and learning contexts. Existing studies frequently address one digital tool or one educational setting, while a systematic comparison of technology–context combinations in agricultural safety training is still lacking. Therefore, this study aims to (i) organize the available evidence through a cross-classification of five digital tool families and five learning contexts; (ii) distinguish combinations supported by direct agricultural evidence from those supported mainly by transferable evidence; and (iii) propose a heuristic Application Priority Score (APS) to compare the potential applicability of the resulting 25 scenarios. The purpose of the APS is not to measure proven effectiveness but to identify combinations that warrant implementation or further empirical investigation.

2. Materials and Methods

This research was started by performing a structured literature investigation conducted exclusively in the Scopus database, which is considered by the authors to have broad

multidisciplinary coverage of peer-reviewed literature in agricultural sciences, engineering, education, and occupational safety. The search strategy was designed to identify studies addressing safety in agricultural and farming contexts in relation to the use of digital and technology-enhanced training tools. To this end, the core concept of safety was systematically combined with terms referring to the agricultural domain and with two main conceptual dimensions: digital training tools and training contexts. The first dimension included five categories of educational technologies:

- immersive technologies (virtual reality, augmented reality, mixed reality, and extended reality);
- simulators and digital twins;
- gamification and serious games;
- e-learning systems (including MOOCs and Learning Management Systems);
- AI-based educational tools such as chatbots and AI tutors.

The second dimension, instead, included the principal context in which safety training may occur, namely:

- formal education (school and university);
- vocational education and training (VET);
- apprenticeships and traineeships;
- lifelong learning and on-the-job training (or Training on The Job, ToTJ);
- peer learning or community of practice settings.

The conceptual structure underlying the search design is summarized in Table 1, where the search strings are organized according to the intersection between the different categories of digital tools and training contexts.

Table 1. Conceptual structure underlying the search design adopted in Scopus, including search wildcards (asterisk) for broader terms not directly related to the agricultural and farming sectors.

Search Dimension	Category	Representative Search Terms or Descriptors
Agricultural safety framework	Core domain	safety AND (agricultur* OR farm*)
Digital training tools	Immersive technologies	virtual reality, augmented reality, mixed reality, extended reality, immersive environment
Digital training tools	Simulation-based approaches	simulation, simulator, digital twin
Digital training tools	Game-based learning tools	serious game, gamification
Digital training tools	Digital learning platforms	e-learning, MOOC, learning management system
Digital training tools	AI-based educational systems	chatbot, AI tutor, intelligent tutoring system, conversational agent
Training contexts	Formal education	school, university, higher education
Training contexts	Vocational education and training	VET, vocational education and training
Training contexts	Apprenticeships and traineeships	apprenticeship, traineeship
Training contexts	Lifelong and work-based learning	lifelong learning, on-the-job training, workplace learning
Training contexts	Peer or community-based learning	peer learning, community of practice, community-based learning

The search architecture was therefore developed as a 5×5 matrix-based framework, in which each group of digital tools was associated with different educational and training

environments relevant to safety learning in agriculture. This approach was adopted to ensure a broad coverage of the scientific literature while preserving conceptual consistency with the objectives of the research. In this way, the framework aimed to capture the diversity of digital solutions currently being explored for agricultural safety training as well as the variety of learning settings in which these tools are implemented and the feedback that was received from users. The full list of search queries is available on Supplementary Material Table S1. After retrieval, all records were exported and subjected to a multi-stage screening process based on several eligibility criteria, which are listed in the following paragraph.

2.1. Study Screening and Eligibility Criteria

After retrieval, studies were screened first by title and abstract and, if considered potentially relevant, by full-text assessment. Studies were considered eligible when they focused on safety in agricultural or farming settings and examined, evaluated, or discussed at least one digital training tool within one or more educational or professional learning context. More specifically, studies were included when they (i) addressed the agricultural or farming sector; (ii) focused on safety, risk prevention, hazard awareness, or occupational training; (iii) investigated one or more of the technological approaches included in the study framework; and (iv) were available as full-text documents suitable for qualitative analysis.

Studies were excluded when they (i) addressed safety in non-agricultural sectors without a clear agricultural application; (ii) focused exclusively on technological development without a training or educational dimension; (iii) dealt with agricultural activities but not with safety-related outcomes; or (iv) consisted of editorials, notes, or other types of publication lacking sufficient methodological or analytical content. The inclusion and exclusion criteria applied during the study selection process are in Table 2, divided by the aim of the criteria adopted for this research.

Table 2. Eligibility criteria adopted for the inclusion and exclusion of studies.

Criterion Domain	Inclusion Criteria	Exclusion Criteria
Sector	Studies focused on the agricultural or farming sector.	Studies addressing safety in non-agricultural sectors without a clear application to agriculture.
Topic	Studies addressing safety, risk prevention, hazard awareness, occupational health, or safety training.	Studies dealing with agriculture in general without a specific focus on safety-related issues.
Educational dimension	Studies examining or discussing education, training, learning, or capacity-building activities.	Studies focused exclusively on technological development without any educational or training dimension.
Technology scope	Studies investigating at least one of the selected digital or technology-enhanced tools.	Studies not involving any of the technology-enabled approaches considered in the study.
Learning context	Studies situated in formal education, vocational education and training (VET), apprenticeships or traineeships, lifelong learning, on-the-job training, or peer/community learning contexts.	Studies unrelated to any learning or training context.
Document type	Full-text publications suitable for qualitative analysis.	Editorials, notes, short commentaries, or publications lacking sufficient methodological or analytical detail.
Accessibility	Studies available in full text.	Records for which the full text was unavailable.

Table 2. *Cont.*

Criterion Domain	Inclusion Criteria	Exclusion Criteria
Relevance to study scope	Studies consistent with exploring digital solutions for safety education and training in agriculture.	Studies outside the conceptual scope of digital safety education and training in agriculture.

The 25 Scopus searches were run in May 2026 and returned 135 records, and after removing 9 duplicate records retrieved through more than one technology–context search combination, 126 unique publications were screened by title and abstract. Records were also excluded because they did not meet the eligibility criteria or were outside the scope of the study, and the full texts of the remaining 38 publications were assessed, with 5 of them subsequently excluded because they lacked a sufficiently clear agricultural safety training or educational dimension. Consequently, 33 publications were included in the final qualitative analysis and classification.

2.2. Evaluation Methodology Across the Taxonomy

In order to obtain a classification and an evaluation of all the possible safety training solutions for agricultural workers involving digital technologies, each scenario has been individually analyzed based on evidence from the scientific literature and previous applications (evidence availability, EA). The parameters that would affect the classification the most have been identified by the authors as the following:

- Cost–benefit feasibility (CBF), where the specific technology has been checked against costs and the dimensions of the possible audience;
- Technology–learner fit (TLF), which is meant to take into account the impact on agricultural workers;
- Inclusivity and accessibility (IA), which also considers language barriers, the impact on seasonal workers and other agricultural contexts like very young workers and elderly workers [12,13].

The four dimensions were selected to represent distinct conditions affecting the application of a digital training tool. EA describes the maturity of the available evidence in agriculture. CBF represents the resources required in relation to the expected number of users. TLF considers whether the interaction mode, complexity, and educational characteristics of the technology correspond to the needs and experience of the target learners. IA considers linguistic, literacy-related, physical, demographic, and digital-access barriers. These dimensions were retained because a specific technology may be supported by scientific evidence but remain impractical, unsuitable for the intended learners, or inaccessible to relevant worker groups. The four dimensions were selected to represent separate conditions affecting the application priority of a digital training tool. EA describes the maturity of the available evidence in agriculture. CBF considers the equipment and software requirements, implementation and customization burden, and the number of users to whom these resources may be distributed. TLF considers task relevance, required digital familiarity, experiential value, and compatibility with the learner’s training stage. IA considers language and literacy demands, physical or sensory accessibility, hardware and connectivity requirements, and suitability for seasonal, migrant, young, older, or otherwise disadvantaged workers. The scenarios were assessed by the author team through consensus using scores, and the resulting assessments should therefore be interpreted as structured author judgments rather than as externally validated estimates. The parameters have therefore been divided into possible scenarios, each with a specific score. The results of this classification are shown in Table 3.

Table 3. Model evaluation methodology for the evaluation of digital tools in agricultural safety training.

Variable	Score	Interpretation Applied to the Agricultural Sector	Explanation
Evidence availability (EA)	1	No direct studies in agriculture	Evidence only from other sectors
	2	1–2 studies in agriculture	Limited proof in agriculture
	3	3–4 studies in agriculture	Evidence can be considered sufficiently present
	4	5–6 studies in agriculture	Studies can be found distributed across all domains
	5	7 or more studies in agriculture	Broadly applied in agriculture
Cost–benefit feasibility (CBF)	1	High-cost solution mainly justified for large groups	The worst-case scenario, requiring high investments
	2	High-cost solution also applicable to small groups	A scenario that can present high costs but is still affordable
	3	Low-cost solution mainly effective for large groups	Technologies that have costs that can be sustained only for large groups
	4	Low-cost solution applicable also to small groups	Technologies that can be applied in all the considered scenarios
Technology–learner fit (TLF)	0.5	Very low expected fit for agricultural target group	Substantial prerequisite skills or adaptation required
	0.75	Low expected fit for the specific agricultural target group	Limited correspondence with learner needs or only marginal advantage over conventional delivery
	1	Neutral fit for the specific agricultural target group	Plausible application
	1.5	High expected fit for the specific agricultural target group	Direct alignment with the target task and learning stage
	2	Very high expected fit for agricultural target group	Strong task alignment, substantial educational benefit
Inclusivity and accessibility (IA)	0.5	Low accessibility or inclusivity	Major barriers related to language, literacy, physical access or device availability
	0.75	Moderate–low accessibility or inclusivity	Several barriers remain and substantial adaptation is required
	1	Neutral accessibility or inclusivity	Neither major accessibility advantages nor major additional barriers
	1.5	High accessibility or inclusivity	Limited barriers and potential adaptation to different languages or literacy levels
	2	Very high accessibility or inclusivity	Broad access across language, literacy, device availability, and user capability

Each parameter has been assessed for each scenario, with the aim of calculating an Application Priority Score (APS), which is an overall index that takes into account all the variables shown in Table 3. The APS was structured as a two-stage multiplicative index. First, EA and CBF were multiplied to define a base application score ranging from 1 to 20;

scoring interpretation is provided in Supplementary Material Table S2, while a detailed score calculation is present in Supplementary Material Table S3. Second, TLF and IA were used as context-dependent modifiers centered on a neutral value of 1. Scores below 1 represented conditions expected to reduce application priority, whereas scores above 1 represented favorable learner-fit or accessibility conditions. Their combined modifier ranged from 0.25 to 4, producing a theoretical APS range of 0.25–80. Finally, digital tools and learning scenarios receive an APS that is obtained by multiplying every single score together in one parameter, ranging from 0.25 to 80 according to Equation (1):

$$\text{APS} = \text{EA} \times \text{CBF} \times \text{TLF} \times \text{IA} \quad (1)$$

The APS was therefore structured as a multiplicative index, and no additional weighting coefficients were applied. The relative influence of the dimensions was instead encoded through their scoring ranges to assign slightly greater influence to the availability of direct agricultural evidence. This calibration was intended to permit comparison across different technology–context combinations while reducing the possibility that a strong result in one dimension could entirely compensate for a severe limitation in another. The scale of the score aims to represent a wide number of possible scenarios, and it might significantly be affected by the barriers that can be faced during agricultural safety training—methodologies that work well in other working contexts might not be fully applicable to agricultural workers such as seasonal personnel and elderly and foreign workers, who might easily encounter language barriers or difficulties in applying digital technologies. Scoring rationale is provided in Supplementary Material, Table S4.

To clarify the methodological workflow adopted in this study, Figure 1 summarizes the sequence followed from literature retrieval to the calculation of the Application Priority Score (APS). The process was organized into three main phases. First, the literature was retrieved and screened through the 5×5 search framework; second, eligible studies were classified within the resulting technology–context matrix, distinguishing between direct agricultural evidence and transferable evidence from adjacent sectors when no agriculture-specific studies were available; lastly, each scenario was assessed through the four APS dimensions.

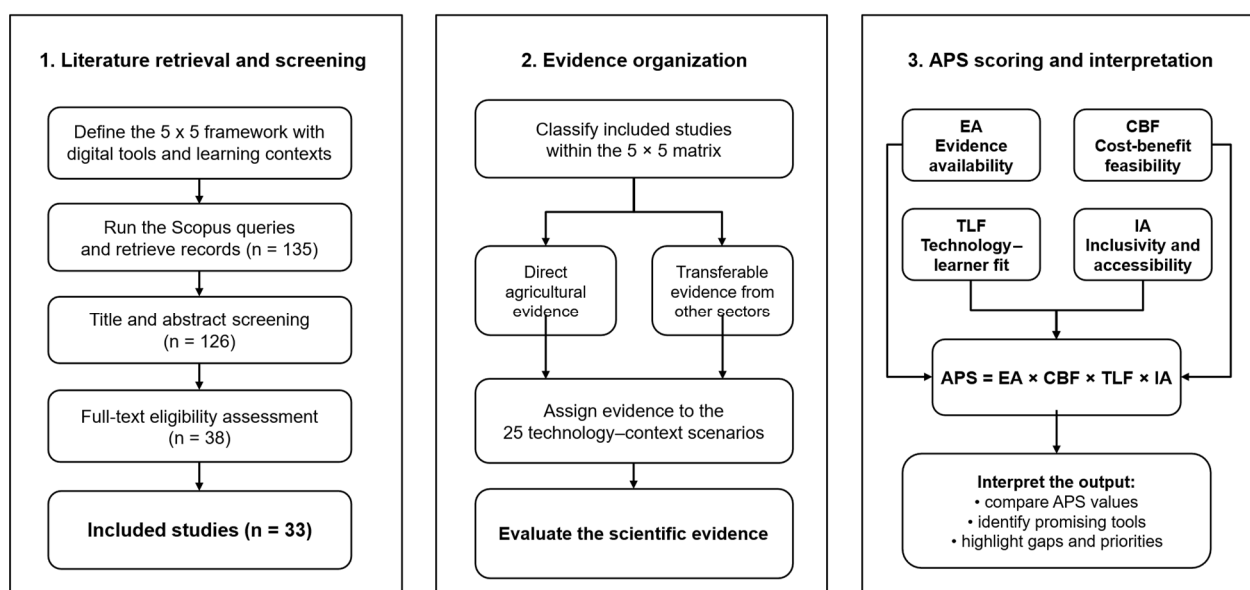


Figure 1. Flowchart of the methodology employed in this study.

This workflow was used to ensure that the final assessment did not depend only on the number of studies retrieved for each query but also on the expected applicability of each digital tool in specific agricultural safety training contexts. In this sense, the APS was not intended as a validated effectiveness measure but rather as a heuristic indicator that supports the comparison across various technology–context combinations.

3. Results

3.1. Distribution of Scientific Evidence Within the 5×5 Framework

The following paragraphs describe the scientific evidence from the application of digital and technological solutions in agricultural safety training. This evidence started to appear in the scientific literature in the 90s [14], when educational resources developed through NIOSH-funded Agricultural Health were being reviewed as Promotion System projects in universities. Resources included CD-ROM materials, computer-based training modules, slide and workbook packages, posters, videos, tractor overturn displays and full-size tractor driving simulators intended for use in educational activities. Several products were specifically designed for vocational agriculture teachers, students and health professionals. This demonstrates the institutional efforts that have been put into place to incorporate simulation and digital tools into agricultural health and safety education, showing that computer-based and simulation-based safety resources were already considered promising educational tools at that time. Since then, several possibilities have arisen [15–18], such as immersive technologies, simulators, and AI-based tools such as chatbots; unfortunately, not all of them have been deeply studied for specific agricultural scenarios, but a large variety of scientific studies are available.

3.1.1. Immersive Technologies in Agricultural Safety Training

The use of immersive technologies is often mentioned, such as the use of augmented reality (AR), to overcome the possibility that workers might lose interest in safety programs and to extend these programs also to children. Studies [19,20] concentrate on the application of this technology to children between 5 and 13 since schools often do not provide safety information regarding production facilities or farms in their courses. The aim of using AR is to make sure that hazardous scenarios can be shown in a realistic way compared to what happens in farm businesses, including the possibility of examining risks through ease of use and digital tools such as zooming in on the scene while walking through a farm using an app. Risk scenarios were selected from an accident database and used in a virtual farm projected on a tabletop, including runover risks involving children, falling from vehicles or being kicked by horses, with the aim of getting useful training information by interviewing participants to understand feasibility, acceptance and implementation challenges.

Among participants in AR safety programs, the feedback is divided into those who recognize the possibility of using technology to have a better impact on children's education about safety but still have doubts regarding the impact on adults and others who do not see an improvement in transferring safety information compared to other methodologies. Results showed that such tools have high implementation potential despite the need to limit the time that children spend on apps in general.

In this context, wearable devices [21] were also investigated for use in greenhouse activities, where a high work intensity is present and workers are exposed to heat stress and posture-related stress. In a recent study, tests involved 30 participants, and data was transmitted in real time on a platform designed for the interactive visualization of information. These wearable sensors were meant to monitor physiological conditions and to contribute to a reduction in fatigue and environmental effects on workers. The integration of wearable devices designed for safety purposes and human–computer interaction (HCI)

systems was identified as a research gap since these instruments were often developed separately and remained independent despite growing attention from the agricultural sector. Devices included wristbands, sensors integrated into clothing and AR glasses in order to collect both environmental and body signals, with data transmissions that relied on wireless connections such as Bluetooth or Wi-Fi. Several parameters were also considered to assess data, like data collection efficiency and ground truth information, validating pose estimation gathered from multiple devices. Safety conditions were then evaluated by monitoring stress events and unsafe postures, while worker experience was measured, with the System Usability Scale (SUS) and NASA-TLX ratings of workload showing a consistent improvement in usability. Study conclusions showed advantages such as the short intervention time, followed by a reduced frequency of posture stress and ease of use of the device, with improved usability if compared with conventional approaches. Recent youth-oriented immersive safety programs also suggest that virtual reality can be implemented beyond isolated prototypes, although evaluation of long-term learning and behavioral outcomes remains necessary [22].

3.1.2. Simulators and Digital Twins

Simulators are often employed in initial safety training with agricultural machinery without having to face the hazards that derive from it [23]. In addition, these tools are employed in education to give the possibility of illustrating agricultural risks to children and students in general. Fathallah [24] used digital ergonomic simulation to assess whether young people can safely operate the tractors commonly used on farms. The study combined photogrammetry and CAD-based tractor models to evaluate whether children could effectively reach major tractor controls on 45 tractors in common use in the United States. The results showed that many controls, especially hand-operated ones, could not be reached safely by the majority of youth operators. The study therefore provides a strong ergonomic basis for reconsidering age-related guidelines for tractor work and for strengthening educational messages concerning youth tractor operation. In this case, simulation functions as a preventive assessment tool supporting safer training and policy decisions. In study by Lleras [25], an open-source tractor driving simulator was developed to study tractor stability and rollover-related safety under controlled conditions [26,27]. The simulator combined a real tractor cab, a custom motion base, a 360-degree high-definition screen, a sound system and a multi-computer network based on open-source software. Its first application focused on tilt perception, showing that operators systematically overestimated roll and pitch, with perceptual errors that may be relevant for defining instability warning thresholds. The study is particularly important because it presents simulation not only as a training environment but also as a research platform for testing driver perception, warning systems and preventive interfaces without exposing operators to real rollover risks. A subsequent study based on the outcomes of the simulator [28] further developed the tool by examining both tilt perception and alert interfaces for tractor instability. In the first experiment, subjects were exposed to different pitch–roll combinations and asked to reproduce them, showing that roll was generally overestimated, while pitch was reproduced more accurately. In the second experiment, the simulator was used to compare the visual, haptic and acoustic warning systems activated when the tractor exceeded a hazardous roll threshold. Participants had to divide their attention between maintaining awareness of vehicle stability and monitoring the surrounding environment, making the task more representative of real field operation.

Digital tools have also been tested. Park [29] used hardware-in-the-loop simulation to estimate the safety benefits of electronic stability control systems for tractor semitrailers. Their system integrated a real pneumatic braking system with the TruckSim simulation

engine, allowing actual hardware to be tested in a virtual driving environment. The platform was used to simulate critical rollover-related maneuvers and was validated against field data from the Vehicle Research Test Center. Results showed that electronic stability control increased the speed thresholds at which critical rollover-related events occurred, thereby improving vehicle stability under dangerous conditions. Although the study belongs more to transport safety than to agricultural education, it remains relevant as an example of simulation-based safety assessment applied to heavy vehicle systems involving tractor semitrailers and automated control technologies.

3.1.3. Serious Games and Gamification

The use of video games for safety purposes has been investigated by research [8]. A study involving seven Italian high schools [30] created a game called “becoming safe” that was provided to students, and then anonymous questionnaires were collected, after which 62.8% of training was considered useful by the students. More recent contributions have further moved from general evidence on digital games towards user-centered and co-design approaches for agricultural safety training, including the analysis of game preferences and the development of game-based solutions for specific machinery-related risks [9]. In another study, Vigoroso [31] investigated gender differences in digital game preferences, with the purpose of supporting the design of more engaging safety training tools for agriculture. An online questionnaire was provided to 137 Italian students with farming experience to explore preferences related to game characteristics and mechanics, genre, and graphic style. The results showed both shared and gender-specific preferences: males and females expressed similar interest in better graphics, dramatic features, better rewards and strategy dynamics, while differences were noted for aspects such as hints and visual styles. Based on these findings, the study proposed a set of practical guidelines for the development of a gamified safety training tool that could generate interest in both genders, highlighting the importance of visual communication adopting a user-centered perspective and showing that the effectiveness of digital safety training in agriculture depends not only on the use of technology itself but also on how game features are designed.

Recent studies on gamified farm safety education have also moved towards co-design and pilot evaluation with adolescents and teachers, confirming the importance of involving target users when designing engaging safety resources [32–34].

3.1.4. E-Learning Systems

Software applications for the reduction of chemical risk is another field that has been explored regarding the use of e-learning apps [35]. A study by Doruchowski [36] developed an application to reduce the risk of contamination from pesticides, meant as an environmental tool for both experts and stakeholders. The results showed that the tool was considered to be easy to use and included a help service with illustrations and references and that the tool can be used to raise awareness with pesticide users regarding the impact of pesticide applications.

3.1.5. AI-Based Education Tools

A program based on chatbots has been developed for grassroots farmers [37] to improve their knowledge of rice farming when chemical use was not avoidable. The program included an interactive lesson with the help of a chatbot to substitute the human role. A pilot exploration was performed to overcome possible complications in knowledge assimilation through interviews and analyses meant to design context-based learning. The chatbot was then used to help farmers of different ages in the selection of appropriate chemicals, promptly providing information or advice to farmers and instructions for mixtures. One of the challenges included the need to break habits that were considered to be unsafe, change

routines based on knowledge and improve the skills related to understanding chemical product labels.

3.1.6. Evidence from Non-Agricultural Contexts with Potential Transferability to Agriculture

Since several intersections in the framework returned limited or no direct agricultural evidence, selected studies from adjacent non-agricultural safety contexts were considered as transferable examples. These studies were not treated as agricultural evidence but as methodological references that may support the future design of digital safety training solutions in agriculture. One relevant group of studies concerns realistic simulators from automotive and construction sectors; although these approaches are mainly used in transport safety contexts [38], they may support agricultural training along with the digital twins and real-time safety management systems that already exist in construction [39]. Finally, non-agricultural serious games tools show how digital environments can be used to increase engagement and support experiential learning, and, as already happens with simulators, they are able to provide repeated exposure to dangerous scenarios without real risk. These examples suggest that, where direct agricultural evidence is still weak, transferable solutions from construction, transport, and general occupational safety may help identify technological pathways that deserve further testing in agricultural contexts.

3.2. Evaluation of the Feasibility of Digital Media for Agricultural Safety Purposes

The feasibility of digital technologies applied to different safety training contexts generated 25 scenarios in which an APS index was evaluated. This work was based on the scientific evidence shown in the previous result paragraphs and was further developed by assessing if the costs derived by the application of the specific digital tool were justified by the size of the expected agricultural worker audience, then verifying if the tool was fit for the audience and, lastly, evaluating if the digital tool was in any way helping or hindering the approach towards particular groups of people. Since the type of audience changes according to the learning context, each scenario needed to be specifically evaluated to understand if the target groups would benefit from the medium and how it could help transfer information to particular worker categories—agricultural safety training should also take into account the presence of workers with disabilities or other disadvantaged workers, exploiting the availability of digital and technological advances to overcome possible additional barriers that would exist in the specific context. The result of the analysis is shown in Table 4. CBF, TLF, and IA were assigned using the operational criteria reported in Table 3, so the qualitative descriptions should not be interpreted as independently demonstrated facts but as concise summaries of structured author judgments.

The assessment of each agricultural safety scenario showed that, as expected, there is no one-size-fits-all training technology but rather a large variety of possible outcomes that are highly influenced by the audience type, number and learning phase. For these reasons, there are no high APS values, which are limited in a range from 1 to 20 and drastically change as they are applied to a different agricultural safety training context despite employing the same technological medium.

A complete overview of the aforementioned evaluation is reported in Figure 2. The different colors indicate if the training tool and training phase represent a good match, from red (bad match) to green (good match).

Table 4. Technology–context assessment. Scores are indicated by parentheses.

Digital Tool Family	Learning Context	Evidence Availability	Cost–Benefit	Technology–Learner Fit	Inclusivity and Accessibility	APS
Immersive technologies	Formal education	4 studies from VR–AR (3)	High costs but still affordable (2)	Familiarity with the medium (2)	Can overcome language barriers (1.5)	18
	VET	Only in other sectors (1)	High costs but still affordable (2)	Familiarity with the medium (2)	Can overcome language barriers (1.5)	6
	Apprenticeship and traineeship	Only in other sectors (1)	High costs, limited customization (1)	Familiarity with the medium (2)	Can overcome language barriers (1.5)	3
	Lifelong learning or ToTJ	Only in other sectors (1)	High costs, limited customization (1)	No benefit of this technology (1)	Benefits would not be clear (1)	1
	Peer, community learning	Only in other sectors (1)	High costs, limited customization (1)	No benefit of this technology (1)	Benefits would not be clear (1)	1
Simulators or digital twins	Formal education	Several studies on digital twins (4)	High costs but still affordable (2)	Students can learn faster (1.5)	Makes basic concepts easier through visualization (1.5)	18
	VET	Only in other sectors (1)	High costs but still affordable (2)	Helps to put theory in practice (2)	Makes basic concepts easier (1.5)	6
	Apprenticeship and traineeship	Only in other sectors (1)	High costs but still affordable (2)	Positive changes in behaviors (2)	Makes basic concepts easier (1.5)	6
	Lifelong learning or ToTJ	Only in other sectors (1)	Personalization is necessary (1)	No significant changes (1)	Not fully applicable (1)	1
	Peer, community learning	Only in other sectors (1)	Personalization is necessary (1)	No significant changes (1)	Not fully applicable (1)	1
Serious games or gamification	Formal education	Several articles on injury prevention (3)	Usable with large groups of users (2)	Higher than in other cases (2)	Ease of use and accessibility (1.5)	18
	VET	Only in other sectors (1)	Usable with large groups of users (2)	Higher than in other cases (2)	Ease of use and accessibility (1.5)	6
	Apprenticeship and traineeship	Only in other sectors (1)	Usable with large groups of users (2)	Customizable (2)	Ease of use and accessibility (1.5)	6
	Lifelong learning or ToTJ	One case study (2)	Usable with large groups of users (2)	Interest only in a few scenarios (1)	Limited match with workers’ needs (1)	4
	Peer, community learning	Only in other sectors (1)	Usable with large groups of users (2)	Interest only in a few scenarios (1)	Limited match with workers’ needs (1)	2

Table 4. Cont.

Digital Tool Family	Learning Context	Evidence Availability	Cost–Benefit	Technology–Learner Fit	Inclusivity and Accessibility	APS
E-learning systems	Formal education	Studies on safety training (2)	Affordable for any kind of group (4)	Users could not be sufficiently engaged (0.75)	Not fully applicable (1)	6
	VET	Only in other sectors (1)	Affordable for any kind of group (4)	Interest limited by the case (1)	Not fully applicable (1)	4
	Apprenticeship and traineeship	Only in other sectors (1)	Affordable for any kind of group (4)	Interest limited by the case (1)	Not fully applicable (1)	4
	Lifelong learning or ToTJ	Only in other sectors (1)	Affordable for any kind of group (4)	Specific content can improve user engagement (2)	Availability in several languages and applications (1.5)	12
	Peer, community learning	Only in other sectors (1)	Affordable for any kind of group and application (4)	Specific content can improve user engagement (2)	Availability in several languages and applications (1.5)	16
AI-based educational tools	Formal education	One study on chatbots (2)	Costs are low for many users (3)	Not fully exploited (1)	No specific beneficial effects (1)	6
	VET	Only in other sectors (1)	Costs are low for many users (3)	Not fully exploited (1)	Exchange of information (2)	6
	Apprenticeship and traineeship	Only in other sectors (1)	Costs are low for many users (3)	Exploited by audience (2)	Exchange of information (2)	12
	Lifelong learning or ToTJ	Only in other sectors (1)	Costs are low for many users (3)	Exploited by audience (2)	Exchange of information (2)	12
	Peer, community learning	Only in other sectors (1)	Large, skilled audience (4)	Exploited by audience (2)	Exchange of information (2)	16

The heatmap in Figure 2 clearly shows that digital twins have drastically different effects according to the safety training phase, with the APS changing dramatically along the rows, especially for lifelong learning and peer or community learning. A similar pattern is also observed in the columns, with interactive or specific training tools representing a better fit for the most experienced agricultural workers.

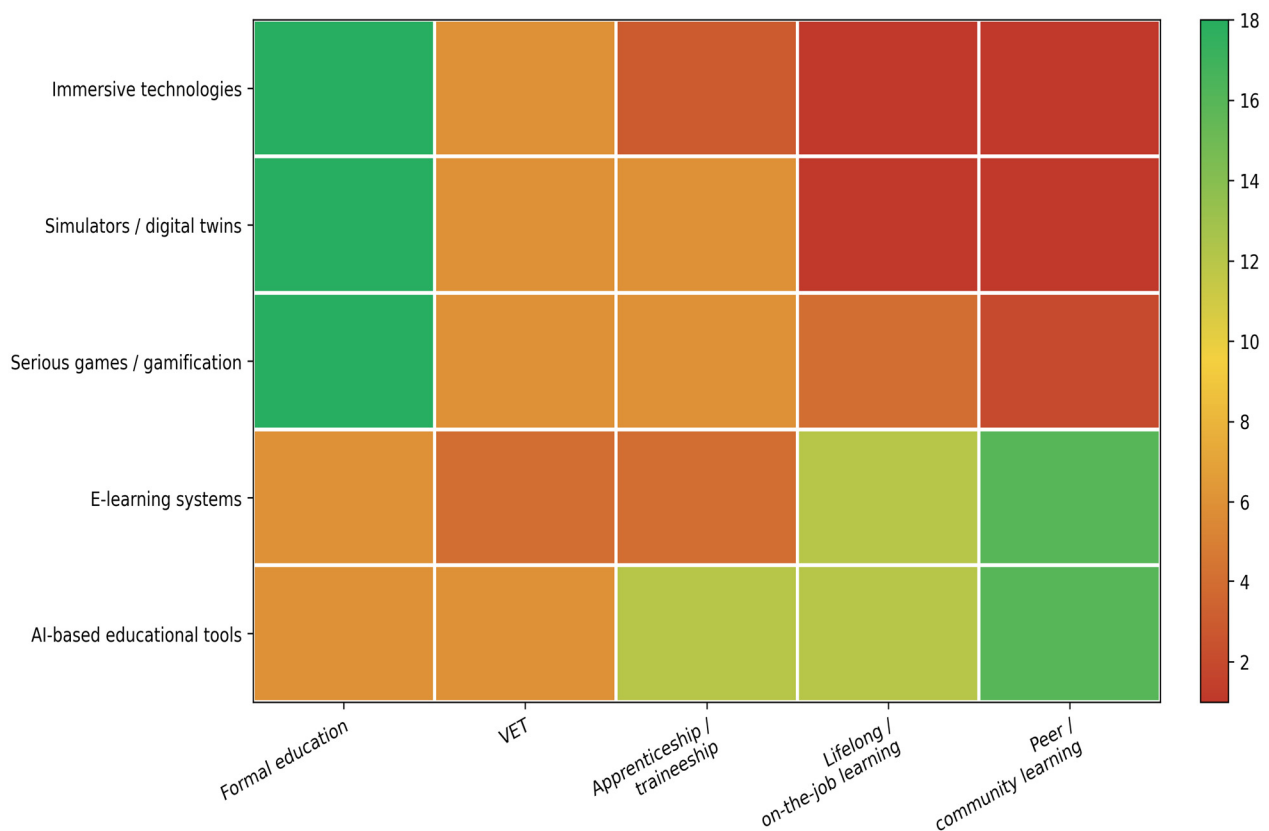


Figure 2. Heatmap of the APS score for each training scenario.

4. Discussion

This research provides a structured framework of how digital and technology-enhanced tools can be employed for safety education and training in agriculture by combining a literature-based taxonomy with a heuristic application priority assessment. The results showed that digital safety training in agriculture is not a homogeneous field but rather a fragmented research area in which different technologies are unevenly distributed across the different learning contexts. Evidence of this was even more visible for immersive technologies, simulators, digital twins, and serious games, especially in formal education or training-like settings. By contrast, applications connected with apprenticeships, lifelong learning, training on the job and peer or community-based learning appeared less developed despite their practical relevance for agricultural work.

The first relevant finding is that the suitability of a digital tool mainly depends on the learning context and on the expected experience of the target users, with immersive technologies and simulators appearing particularly promising in formal education and vocational training, where learners may have limited direct exposure to hazardous agricultural tasks. In these contexts, digital tools can reproduce hazardous working conditions, machinery interactions, rollover scenarios for agricultural self-propelled machinery, ergonomic constraints, or environmental hazards without exposing learners to real risk. Their value is therefore linked to safe experiential learning, repeated practice, and visual understanding of complex situations. However, the same technologies become less attractive in lifelong or on-the-job contexts, where workers often need rapid, task-specific, and low-cost support rather than complex simulated environments.

The second important result concerns the role of accessibility and inclusivity since agricultural safety training is often aimed at heterogeneous groups, including seasonal workers, migrant workers, young learners, older operators, and workers with different levels of literacy and digital familiarity. For this reason, the effectiveness of digital training

cannot be assessed only in terms of technological complexity; barriers related to cost, equipment availability, digital skills, language, and physical access had to be assessed as well. Conversely, some simpler tools, such as e-learning modules, mobile applications, or chatbots, can provide lower levels of immersion but greater flexibility and accessibility for any kind of agricultural worker; this is particularly relevant since research showed that game-based training does not become inclusive only by being digital or interactive [4,31].

The cross-classification confirms previous technology-specific findings and extends them by showing that the expected value of a digital tool changes according to the learning context. Immersive systems, simulation, and serious games have generally been discussed in terms of realism, engagement, or learning performance. The present framework adds a contextual layer by considering whether these characteristics remain advantageous for formal students, vocational learners, apprentices, experienced workers, or peer-learning communities.

The APS also differs from evaluation approaches centered exclusively on usability or technology acceptance. It combines the availability of agricultural evidence with feasibility, learner fit, and accessibility. Its purpose is not to replace usability testing, learning-outcome assessment, or formal multi-criteria decision analysis but to support an initial comparison of scenarios before empirical implementation. The APS framework reflects this generalized trade-off, where the highest scores do not automatically correspond to the most advanced technologies but to the combinations in which evidence, feasibility, learner fit, and inclusivity are reasonably aligned. In agricultural contexts, in fact, the most suitable solution may be a modular and context-sensitive mix of tools: simulators and immersive systems for early-stage learning and high-risk scenarios; serious games for engagement and hazard awareness; e-learning for structured and scalable knowledge transfer; and AI-based tools or chatbots for continuous, situated, and multilingual support. The interpretation of high or intermediate APS values depends, in this context, on the origin of the supporting evidence—for instance, combinations supported by direct agricultural studies may be considered supported priorities within the limitations of the available study designs; by contrast, combinations based mainly on evidence from other sectors should be considered exploratory priorities. In these cases, a favorable APS indicates a plausible alignment between the technology and the learning context but does not demonstrate effectiveness in agriculture. These combinations should therefore be regarded as candidates for pilot testing and agricultural validation.

The analysis also highlights an important research gap, in which several promising technology–context combinations are still supported mainly by evidence from non-agricultural sectors. This is especially relevant for digital twins, AI-based tutoring systems, and community-based digital learning. Construction, transport, and general occupational safety provide useful transferable examples, but agricultural validation remains necessary given that farms are often characterized by small and heterogeneous enterprises, a variable seasonal workforce, operations that depend on seasonality and a strong interaction between formal and informal learning. Therefore, tools developed in other sectors cannot simply be transferred without adaptation; they need to be redesigned according to agricultural tasks, worker profiles, organizational constraints, and local safety cultures.

From a practical perspective, the findings suggest that future digital safety training in agriculture should be designed around the training situation rather than around the technology itself, without following technological trends, and where higher costs do not automatically correspond to better results. Formal education may benefit from immersive environments, digital games, and simulators that support a first exposure to hazards, while vocational training and apprenticeships may require tools that connect theory with practical action, such as task-based simulation, guided scenarios, or interactive modules. Lifelong

and on-the-job training may benefit more from short, mobile, and context-aware resources, including chatbots, visual checklists, or microlearning units, and peer-based contexts may require tools that support an exchange of experience, multilingual communication, and collective learning rather than individual performance alone. From a practical perspective, the framework may be used by agricultural schools and universities, vocational training providers, extension services, occupational safety professionals, farm organizations, public agencies, machinery manufacturers, technology developers, and funding bodies. It may support an initial comparison of alternative training tools, the identification of evidence gaps, and the prioritization of pilot applications. However, APS results should be combined with local needs assessment, available resources, and consultation with trainers and prospective users.

Some limitations must however be highlighted in this approach. First, the search was conducted based exclusively on existing research outcomes, while relevant technical reports, extension materials or non-indexed training resources may not have been captured. This is particularly important in agriculture, where practical safety education is often developed by extension services, public agencies, and professional organizations rather than only through academic publications. Second, the APS is a heuristic and qualitative score and should not be interpreted as a validated measure of effectiveness; the score, in fact, was designed to support comparison and discussion across technology–context combinations, but it depends on expert judgment and on the available evidence. Third, several studies included in the analysis were not designed specifically to evaluate learning outcomes or injury reduction, which limits the possibility of drawing strong conclusions on effectiveness. A further limitation concerns the subjective component of the CBF, TLF, and IA ratings. Although predefined criteria and a scenario-level evidence table were used, the scores were assigned by the author team through consensus and were not validated through independent ratings, an external expert panel, or stakeholder consultation. The selected scoring ranges and the multiplicative aggregation rule may also affect the resulting APS values. In particular, a one-level change in a component score may produce a nonlinear change in the final result. For this reason, small APS differences should not be interpreted as statistically meaningful, and external validation remains necessary.

Lastly, it must be said that the APS values depend on the selected score categories and on the multiplicative aggregation rule; therefore, since the index is exploratory and based on evidence-informed judgments, no formal sensitivity analysis could be performed, and small differences between APS values should consequently not be interpreted as statistically meaningful. Despite these limitations, the proposed framework offers a useful basis for organizing a fragmented field and identifying priorities for future research. Further studies should move from conceptual or prototype-level work toward empirical validation, including usability testing, pre–post learning assessment, behavioral indicators, and long-term effects on safety practices. Particular attention should be paid to vulnerable and hard-to-reach worker groups, multilingual design, low-literacy communication and the integration of digital tools into real agricultural safety management processes.

5. Conclusions

This study proposes a cross-classification framework to analyze digital and technology-enhanced tools for safety education and training in agriculture across five learning contexts. Although the field is growing and research articles keep trying new technological solutions applied to different agricultural safety training phases, the framework remains fragmented, with evidence concentrated in a limited number of contexts. Immersive technologies, simulators, digital twins, and serious games appear particularly relevant for formal education and early-stage training, where safe exposure to hazardous scenarios is

essential. E-learning systems and AI-based tools, including chatbots, appear more suitable for continuous, flexible, and accessible support, especially in lifelong, on-the-job, and community-based learning contexts.

The Application Priority Score (APS) model provided a structured way to compare the potential applicability of different solutions by considering evidence availability, cost–benefit feasibility, technology–learner fit, and inclusivity or accessibility. The results confirm that no single digital tool can be considered universally suitable for agricultural safety training; instead, the value of each technology depends on the target users, their experience level, the training setting, and the practical barriers that characterize agricultural work.

The main contribution of this paper is therefore not the identification of one best technology but the proposal of a context-sensitive framework for selecting and prioritizing digital safety training tools in agriculture. The practical contribution is a transparent procedure that may support preliminary comparison and prioritization of potential applications without replacing empirical testing or local needs assessment. Future developments should focus on empirical validation, worker-centered design, multilingual and accessible interfaces, and the adaptation of transferable solutions from other high-risk sectors to the specific conditions of agricultural work. Future research should also investigate hybrid training pathways in which different tools are combined according to the learner’s experience, agricultural task risk level and organizational context.

Supplementary Materials: The following supporting information can be downloaded at: <https://www.mdpi.com/article/10.3390/agriculture16151634/s1>, Table S1: search queries; Table S2: scoring rubric; Table S3: APS scores; Table S4: scoring rationale. Supplementary Tables supporting the search strategy, study classification, and APS scoring procedure are available on request.

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Abbreviations

AI	Artificial Intelligence
AR	Augmented Reality
APS	Application Priority Score
EA	Evidence Availability
CAD	Computer-Aided Design
CBF	Cost–Benefit Feasibility
CD-ROM	Compact Disc Read-Only Memory
HCI	Human–Computer Interaction
IA	Inclusivity and Accessibility
ILO	International Labour Organization
LMS	Learning Management System
MOOC	Massive Open Online Course
MR	Mixed Reality
NASA-TLX	NASA Task Load Index

NIOSH	National Institute for Occupational Safety and Health (USA)
SUS	System Usability Scale
TLF	Technology–Learner Fit
ToTJ	Training on The Job
VET	Vocational Education and Training
VR	Virtual Reality
XR	Extended Reality

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