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Review Article

The Effectiveness of Information and Communication Technology in Science Learning in Elementary Schools

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Abstract. The purpose of this study is to explore and synthesize the latest empirical evidence (2020–2025) regarding the effectiveness of using Information and Communication Technology (ICT) in improving the quality of Natural Science (IPA) learning at the Elementary School (SD) level. Effectiveness evaluation was conducted multidimensionally, covering improvements in cognitive learning outcomes, the development of science process skills (SPS) as a psychomotor dimension, and affective impacts (motivation, engagement, and inclusion). This study followed a systematic protocol to ensure transparency and disclosure. The synthesis of studies indexed by Scopus and SINTA showed that ICT has significant and beneficial effects, especially when combined with constructivist learning models such as Problem-Based Learning (PBL) or Project-Based Learning (PjBL). Cognitively, ICT has been shown to substantially improve conceptual understanding (with a high N-gain score). Psychomotorically, simulation and immersive reality technology are very effective in training integrated SPS. In addition, ICT plays a crucial role in the affective dimension, serving as an inclusion tool that personalizes teaching, increases motivation, and supports the active participation of students with special educational needs (SENs). This study concludes that effective ICT implementation requires improving teachers' pedagogical competence in integrating interactive technologies (such as augmented reality, virtual reality, and artificial intelligence-based adaptive systems) with active learning strategies.

Keywords: Learning Effectiveness, Inclusion, Science Process Skills, Information Communication Technology.

1. Introduction

Science education at the elementary school level serves as an important foundation for the development of students' science literacy in the 21st century [1]. Science is defined as a dynamic relationship between scientific knowledge, scientific values, and scientific methods [2]. Its main goal is to equip students with the ability to understand the world around them through investigation and logical reasoning [3]. Nevertheless, science teaching in elementary schools faces significant challenges [4]. Students at this level are in the stage of cognitive development where their thinking tends to be still concrete [5]. Most science material, especially that involving abstract concepts such as force, energy, and microscopic phenomena, is often difficult to understand because it is presented without adequate visualization or real-world experience [6]. These limitations, which are often referred to as obstacles in contextual and engaging presentation [7], contribute to students' low conceptual understanding and critical thinking skills [8]. Therefore, innovation in science learning is needed to strengthen students' understanding of concepts [9].

The rapid advancement of science and technology (IPTEK) requires a transformation in the education system, which requires teachers to apply technology in active and enjoyable learning [10]. Information and Communication Technology (ICT), or Educational Technology (EdTech), has become an important instrument for overcoming various learning barriers [11]. The integration of ICT in elementary science learning offers a solution to overcome abstract constraints. ICT enables the provision of interactive media that triggers engagement, provides feedback, and facilitates the exploration of virtual environments [12]. For example, the use of physics simulation applications such

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as PhET allows students to manipulate variables in real-time (e.g., force, mass, and acceleration), giving them a deeper visual understanding than just reading from a textbook [13]. The shift from passive learning to learning that facilitates direct interaction between students and visual or manipulative representations is a key prerequisite for improving the effectiveness of science learning [14].

To meet the research standards published in reputable journals (Scopus/SINTA), the evaluation of ICT effectiveness must be multidimensional and supported by strong quantitative metrics. This study determined that effectiveness is measured through three main dimensions of learning outcomes: (a) measured through improved conceptual understanding and cognitive learning outcomes, often using an N-gain (normalized gain) score to demonstrate the effectiveness of an intervention [15], (b) measured through Science Process Skills (SPS) and Critical Thinking Skills [16], and (c) measured through increased learning motivation, engagement, and ICT contribution to educational inclusion [17].

Particular emphasis is placed on the use of robust quantitative metrics, such as N-gain, as such results provide the empirical evidence necessary to prove their effectiveness academically, in accordance with international publication standards [18]. The main objective of this study is to evaluate and critically synthesize the latest empirical findings (2020-2025) to identify the most crucial technologies, pedagogical models, and effectiveness indicators in the implementation of ICT in elementary science [19]. ICT, as a component of Educational Technology (EdTech), encompasses a wide range of tools and systems designed to mediate the learning process and overcome learning barriers [20]. In the last decade, the role of ICT has evolved from just a presentation medium (educational videos or interactive slides) to an intelligent and adaptive learning system [21]. Recent studies show a trend toward systems that support personalized learning. Adaptive Learning Systems (ALS) and the use of Artificial Intelligence (AI) are increasingly being researched [22]. AI in education enables adaptive instruction in real-time, providing individualized support and feedback to students [23]. The utilization of this kind of innovative technology not only improves academic performance but also significantly triggers student motivation and engagement [24].

Science Process Skills (SPS) is a core competency in science learning in the 21st century. SPS allows students to act like scientists, not just memorize facts. SPS includes basic process skills, such as observing, measuring, classifying, and communicating, as well as integrated process skills, such as formulating hypotheses, determining variables, interpreting data, analyzing, and synthesizing data [25]. The development of SPS, especially integrated skills, is very important in elementary/secondary schools [26]. ICT plays an important role here, as simulation technologies and virtual environments (such as virtual labs) offer an ideal way to train integrated SPS [27]. Students can design and conduct virtual experiments, collect data, and interpret the results, activities that are often difficult to replicate in elementary school physical laboratories due to resource or security limitations [28].

To ensure that the findings of these studies are relevant and credible, the literature review must adhere to strict standards of scientific publications. Research articles must be sourced from Scopus or SINTA 2 indexed journals or above, demonstrating methodological rigor and a transparent peer-review process. The main criterion used in this review is publication time restrictions (2020–2025) to reflect the most current curriculum trends, technologies, and contexts [29], [30]. This approach uses a Systematic Literature Review (SLR), requiring the study to follow structured, transparent, and replicable steps, as suggested by the PRISMA protocol.

2. Implementation Method

2.1 Research Design: Systematic Literature Review (SLR)

This study uses a Systematic Literature Review (SLR) design. The SLR method was chosen because it provides a scalable and transparent framework for identifying, evaluating, and synthesizing data from various empirical research outcomes (especially quasi-experimental studies and developmental research) in depth. This approach goes beyond traditional literature review by implementing strict protocols to reduce bias in the selection process.

2.2 Data Search Protocols and Strategies

Search and reporting protocols are based on recommended frameworks (PRISMA-P), ensuring that all steps from identification to inclusion are clearly documented. Literature searches were conducted on major databases that include highly reputable journals, namely Scopus, Web of Science, and local academic databases that include SINTA-indexed journals. The publication time limit is set from 2020 to 2025. The combination of keywords used in Indonesian and English includes terms such as: effectiveness, ICT, primary school, science, SPS, N-gain, Scopus, SINTA 2020–2025, EdTech, adaptive learning, and interactive simulation.

Table 1. Present the common protocols followed in the SLR process

Stages	Procedure Description (2020–2025)	Justification
Identification	Initial searches on Scopus, SINTA, WoS used specific keyword combinations related to ICT, ELEMENTARY SCIENCE, and effectiveness.	Ensure an indexed database, up-to-date data, and relevance of core topics [31].
Screening	Screening based on titles and abstracts to ensure a focus on ICT in the context of science learning at the elementary/middle school level and effectiveness assessment.	Eliminate studies that are not relevant to the level of basic education (e.g. junior high school/high school) [32].
Credentials	Full-text screening, evaluating methodological rigor (quasi-experimental design, valid instruments) and availability of quantitative effectiveness metrics.	Ensure the quality and validity of the empirical evidence included.
Inclusion	The number of final articles included in the thematic synthesis and thematic meta-synthesis processes.	Transparency and replication of the selection process [33].

2.3 Inclusion and Exclusion Criteria

The inclusion criteria for the analyzed studies were: (a) the research article focuses on the use of ICT (including multimedia, simulation, or adaptive systems) in the context of science learning in elementary schools (SD/MI). (b) Peer-reviewed publications are indexed by Scopus or SINTA. (c) The time range of publication is between 2020 and 2025 [34]. (d) Presenting clear effectiveness metrics, both quantitative (N-gain, t-test, SPS scores) and qualitative (motivation, engagement, inclusion) [35]. Exclusion Criteria include: studies published before 2020; non-research articles (opinions, book reviews); and studies that focus on higher education levels (junior high school/high school) unless their relevance to the context of elementary school is proven to be very strong.

2.4 Data Extraction and Synthesis Procedures

After the selection stage, the data is extracted. This process includes the identification of key variables: the type of ICT used, the integrated learning model, the research subject (elementary/middle school students), the effectiveness metrics measured, and the quantitative results (e.g., the average pre-test and post-test score of N-gain). To ensure reliability, the initial screening process involves at least one independent reviewer.

Data analysis is carried out through thematic synthesis to identify common patterns in ICT types and their impacts, as well as thematic meta-synthesis, especially to compile and compare quantitative results such as N-gain from relevant effectiveness (quasi-experimental) studies [36].

3. Result and Discussion

3.1 Trend Map of ICT Implementation in Elementary Science (2020–2025)

Literature analysis for the period 2020–2025 shows a significant shift in the types of ICT used in elementary science learning. Initially, the focus may be on basic digital multimedia such as educational videos and interactive slides. However, recent trends show an increase in the adoption of technologies that offer higher levels of interaction and personalization, which directly addresses the problem of understanding abstract concepts. The most prominent and proven effective technologies in the current literature include:

1. Interactive Simulations: A prime example is physics simulation applications such as PhET, which allow students to simulate the motion of objects and observe the interaction of force, mass, and acceleration in real-time.
2. Immersive Reality: Including Augmented Reality (AR), Virtual Reality (VR), and virtual labs, which serve to concretize abstract concepts and offer environmental exploration [37].
3. Adaptive Systems and AI: The use of Intelligent Tutoring Systems or Artificial Intelligence (AI)-based applications that provide individualized instruction and real-time feedback [38].

This type of ICT is considered effective because it can help students understand abstract science concepts in a more concrete and fun way [39].

Table 2. Summarizing the ICT taxonomy that has been found to be effective in Elementary Science Learning (2020–2025)

ICT Type	Specific Examples	Key Functions	Main Impact	Ref.
Interactive Simulation	PhET Simulation, Laboratorium Virtual	Visualize complex variable interactions, enabling real-time manipulation	Overcoming abstract concepts; Improvement of Critical Thinking Skills	[40]
Immersive Reality	Augmented Reality (AR), Virtual Reality (VR)	Provide environmental exploration and contextual experiences that are difficult to access	Increased Engagement, Materialization	[41]
Adaptive Learning (AI)	Intelligent Tutoring Systems, an AI-based application	Personalize instructions, provide individualized learning paths and real-time feedback	Increased Motivation, Inclusion Support (SENs), Academic Performance	[42]
Basic Digital Multimedia	Educational Videos, Interactive E-books, Quiz Apps	Material supplements, formative assessments, interest enhancers	Understanding of Basic Concepts, Learning Interest	[43]

3.2 Cognitive Effectiveness Evaluation: Improving Conceptual Understanding

A synthesis of quantitative data from effectiveness studies shows that the use of ICT consistently results in higher learning outcomes compared to traditional methods. The effectiveness of ICT is most strongly seen in bridging the gap between abstract material and concrete thinking of elementary school students. One of the strongest pieces of evidence regarding the cognitive effectiveness of ICT is seen in quasi-experimental studies that measure improved critical thinking skills, which are an integral part of the high-level cognitive domain. For example, a study using interactive multimedia reported an average pre-test score of 34.75 and a post-test score of 82.05 (Taufiq, 2020). This increase was measured using an N-gain score, which reached 0.75 in the experimental group, categorized as "high". These results show that ICT not only improves scores but also achieves a substantial level of effectiveness in encouraging a deeper understanding of concepts.

The main advantage of ICT in the cognitive dimension is its ability to offer visual and manipulative representations. Students who have difficulty understanding Newton's laws through oral explanations or textbooks can visually observe and manipulate variables in simulations, which directly supports their cognitive processes in understanding cause-and-effect relationships. Other studies have also concluded that science learning using certain media (e.g., digital comics) is better than conventional media in terms of understanding concepts and application [44].

3.3 Evaluation of Psychomotor Effectiveness: Impact on Science Process Skills (SPS)

ICT has proven to be very relevant in training Science Process Skills (SPS). Basic SPS (observation, measuring) and integrated SPS (formulating hypotheses, interpreting data) can be trained effectively through a simulated environment. ICT transforms the role of students from consumers of information to active investigators. A study examining the effectiveness of interactive multimedia in improving critical thinking skills strongly associated with integrated SPS found that the highest increase in N-gain occurred in the indicator "Formulating alternative solutions," reaching a value of 0.86. This indicates that ICT, particularly through simulations and virtual labs, facilitates students' training in data analysis and solution formulation skills, which are key components of an integrated SPS. By using ICT, obstacles that are often experienced in elementary schools, such as the limitations of laboratory equipment and the risk of experiments, can be overcome [45]. Students can run virtual experiments over and over again, test hypotheses, and interpret the results, without physical limitations, thus effectively encouraging the development of their scientific process skills. The ability to view and manipulate variables in real-time (as in PhET) directly supports basic and integrated SPS training.

3.4 Evaluation of Affective Effectiveness: Motivation, Engagement, and Inclusion

The evaluation of the effectiveness of ICT in elementary science learning is not only limited to cognitive and psychomotor outcomes but also includes affective dimensions, namely motivation, engagement, and inclusion. Meta-analysis showed a favorable effect for experimental groups that used ICT in science learning, especially in supporting student diversity. The use of ICTs, particularly mobile devices (tablets or mobile devices), has been shown to generate greater motivation among students. ICT positively affects students' learning interest and motivation questionnaire scores. This increase in motivation is not only superficial. By utilizing ICT, teachers can design activities tailored to students' individual interests and abilities, ultimately increasing their autonomy and active participation in the learning process.

One of the most significant findings in the current literature is the role of ICT in creating educational equity, especially for students with Special Educational Needs (SENs). ICT serves as an important tool for attention to diversity. AI-based adaptive systems allow for personalization of instructions. These systems can tailor the material and learning pace according to the specific needs of the student, providing individual support and addressing certain learning difficulties, such as dyslexia, through intelligent tutoring systems. The personalization of this instruction ensures that ICT not only improves average performance but also reaches students who may be marginalized by traditional methods. Effective use of ICT can foster meaningful and high-quality inclusion by supporting the active participation of SEN students.

Table 3. Synthesis of Key Metrics and Indicators of ICT Effectiveness in Elementary Science

Dimension of Effectiveness	Measurement Indicator	Positive Outcome Range (2020–2025)	Implications for Elementary School	Ref.
Cognitive	N-Gain Score Pemahaman Konsep	N-gain hingga 0,75 (Kategori Tinggi)	Overcoming the difficulty of understanding abstract concepts through visualization.	[46]
Psychomotor Skills (SPS)	Skor Keterampilan Berpikir Kritis, Observasi Eksperimen	Peningkatan N-gain tertinggi pada indikator "Merumuskan alternatif penyelesaian" (0,86)	Develop data investigation and analysis skills, transforming the role of students into scientists.	[47]
Affective (Motivation)	Angket Motivasi, Keterlibatan Partisipasi	Efek yang menguntungkan (*favorable effect*) pada kelompok eksperimen TIK.	Increase interest, autonomy, and create an enjoyable learning experience.	[48]
Inclusion	Student Participation Rate SENs, Quality of Personalization	ICT supports effective self-creation and increased active participation through adaptive systems.	Creating a more inclusive and equitable learning environment.	[49]

3.5 Challenges and Key Factors for Successful Implementation

The high effectiveness of ICT depends on how the technology is pedagogically integrated. There is strong agreement in the literature that digital media, such as virtual labs and AR/VR, become effective only when combined with constructivistic learning models such as PBL, Discovery Learning, PjBL. These models provide a framework that drives inquiry, so that technology is used as an investigative tool, not just a substitute for lectures. However, the implementation of ICT in elementary schools faces several main obstacles:

1. Teacher Competence: The main problem experienced is the lack of teachers' understanding of the effective implementation of technology in science learning. Teachers may only be limited to presenting materials or conventional field practices, whereas ICT can be used to display more sophisticated educational videos or interactive slides.
2. Student Readiness and Dependency: Although ICT increases autonomy, some experimental studies have noted that students are not used to independent learning and still tend to depend on teacher/lecturer instruction (Taufiq, 2020). ICT implementation must be accompanied by self-reliance training.
3. Infrastructure Limitations: Although not explicitly measured in effectiveness metrics, uneven availability of devices, connectivity, and technical support across regions are structural challenges in achieving ICT effectiveness nationwide.

A key factor of success lies in the understanding that technology must be used to strengthen pedagogical methodologies. The optimal implementation of ICT in elementary science must be able to connect technology, emotions, and student diversity , thereby facilitating effective and meaningful educational inclusion [50].

4. Conclusion

Based on a systematic literature review of Scopus and SINTA-indexed journals for the 2020–2025 period, it can be concluded that the use of Information and Communication Technology (ICT) shows significant and multidimensional effectiveness in science learning in elementary schools. This effectiveness goes beyond the improvement of cognitive achievement alone, extending to the psychomotor (SPS) and affective (motivation and inclusion) dimensions. The most effective technologies are those that offer interactive and manipulative experiences, such as PhET simulations, Virtual Labs, and Immersive Reality (AR/VR), as these technologies manage to concretize abstract science concepts. Empirical evidence shows cognitive effectiveness through high N-gain scores (up to 0.75) and integrated SPS increases (with N-gain up to 0.86 on the indicators of alternative formulation of settlement) (Taufiq, 2020). Affectively, ICT has been shown to have a beneficial effect, especially as an inclusion tool that facilitates personalization and increases the participation of students with special needs. However, optimal effectiveness is only achieved when ICT is intentionally integrated with constructivist learning models such as PBL and PjBL.

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6. Declaration

Author contributions and responsibilities - The authors made substantial contributions to the conception and design of the study. The authors were responsible for the data analysis, interpretation, and discussion of the results. The authors read and approved the final manuscript.

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7. How to Quote

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