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Kaskelen, 2026

Impact of Smart Technologies on Teaching Sustainable Chemistry: A Focus on Biohumus Production

Abdybekova Azhar

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for the degree of

MASTER OF EDUCATIONAL SCIENCES
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«SDU University»
Department of Pedagogy of Natural Sciences

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Kaskelen, 2026

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LIST OF ABBREVIATIONS

AI — Artificial Intelligence

ACS — American Chemical Society

AR — Augmented Reality

C:N — Carbon-to-Nitrogen ratio

GSC — Green and Sustainable Chemistry

ICT — Information and Communication Technologies

IMRAD — Introduction, Methodology, Results, and Discussion

IoT — Internet of Things

IUPAC — International Union of Pure and Applied Chemistry

MCQ — Multiple Choice Questions

NPK — Nitrogen, Phosphorus, and Potassium

PBL — Problem-Based Learning

PCK — Pedagogical Content Knowledge

pH — Potential of Hydrogen

RQ — Research Question

RSC — Royal Society of Chemistry

SDG — Sustainable Development Goals

STEM — Science, Technology, Engineering, and Mathematics

UNESCO — United Nations Educational, Scientific and Cultural Organization

VR — Augmented Reality / Virtual Reality

ABSTRACT

This paper investigates how smart Internet of Things (IoT) sensors might help in teaching sustainable chemistry through a biohumus production project. The research attempts to answer the following questions: how do smart technologies increase the effectiveness of sustainable chemistry teaching; to what extent do digital tools enhance students' understanding of biohumus production; and which technologies are the most effective in enhancing green chemistry knowledge and skills?

The study employed a mixed-methods design. The quantitative phase involved a quasi-experimental pre-test/post-test design with 72 third-year undergraduate chemistry students at SDU University, Kaskelen, Kazakhstan (n=36 experimental; n=36 control). The experiment group applied an IoT intelligent soil detector during lab sessions; the control group applied conventional measuring tools. The qualitative phase consisted of an online survey of 15 practicing chemistry teachers, analysed using thematic analysis.

Results illustrated that the learning gains of the experimental group were significantly higher than that of the control group, $U = 306$, $p < .001$, $r = .529$. Post-test accuracy was 81.9% for the experimental group and 60.8% for the control group. Qualitative findings revealed four themes: real-time data visualization as IoT's core teaching value; natural complementarity between biohumus and smart technology; structural barriers to adoption; and a recommendation to start small.

This Central Asian study offers empirical evidence from a context underrepresented in international literature and provides a replicable instructional model for technology-enhanced sustainable chemistry teaching. A preliminary version was presented at ICEDU 2026 in Bali, Indonesia.

Keywords: *smart technologies, IoT, sustainable chemistry, biohumus production, green chemistry education, Kazakhstan*

АҢДАТПА

Бұл мақала IoT смарт сенсорларының биогумус өндіру жобасы арқылы тұрақты химияны оқытудағы рөлін зерттейді. Зерттеу мынадай сұрақтарға жауап іздейді: смарт технологиялар тұрақты химияны оқыту тиімділігін қалай арттырады; цифрлық құралдар студенттердің биогумус өндірісін түсінуіне қандай дәрежеде ықпал етеді; және жасыл химия білімі мен дағдыларын дамытуда қандай технологиялар ең тиімді болып табылады?

Зерттеуде аралас әдістер қолданылды. Сандық кезең Қазақстанның Қаскелен қаласындағы ҚДУ университетінің 72 үшінші курс химия студенттерімен (n=36 эксперименттік; n=36 бақылау) квазиэксперименттік алдын ала/қорытынды тест дизайнын қамтыды. Эксперименттік топ зертханалық сабақтарда IoT интеллектуалды топырақ детекторын пайдаланды; бақылау тобы дәстүрлі өлшеу құралдарын қолданды. Сапалық кезең тақырыптық талдау арқылы талданған 15 практикующий химия мұғалімінің онлайн сауалнамасынан тұрды.

Нәтижелер эксперименттік топтың оқу жетістіктері бақылау тобына қарағанда айтарлықтай жоғары екенін көрсетті: $U = 306$, $p < .001$, $r = .529$. Қорытынды тест дәлдігі эксперименттік топта 81,9%, бақылау тобында 60,8% құрады. Сапалық нәтижелер төрт тақырыпты анықтады: нақты уақыттағы деректерді визуализациялау IoT-тің негізгі оқыту құндылығы ретінде; биогумус пен смарт технологияның табиғи үйлесімділігі; қабылдауға кедергі болатын құрылымдық тосқауылдар; және шағын бастамадан бастау ұсынысы.

Орталық Азияда жүргізілген бұл зерттеу халықаралық әдебиетте аз ұсынылған контексттен эмпирикалық дәлелдер ұсынады және технологиямен жетілдірілген тұрақты химияны оқыту үшін қайталануға болатын нұсқаулық моделін қамтамасыз етеді. Алдын ала нұсқасы 2026 жылы Индонезияның Бали қаласында өткен ICEDU 2026 конференциясында ұсынылды.

Түйін сөздер: *смарт технологиялар, IoT, тұрақты химия, биогумус өндірісі, жасыл химия білімі, Қазақстан*

АННОТАЦИЯ

Данная работа исследует роль смарт-сенсоров IoT в обучении устойчивой химии в рамках проекта по производству биогумуса. Исследование направлено на ответы на следующие вопросы: каким образом смарт-технологии повышают эффективность обучения устойчивой химии; в какой мере цифровые инструменты способствуют пониманию студентами процессов производства биогумуса; и какие технологии наиболее эффективны для развития знаний и навыков в области зелёной химии?

Количественный этап включал квазиэкспериментальный дизайн с предварительным и итоговым тестированием с участием 72 студентов третьего курса химического факультета Университета СДУ в Каскелене, Казахстан (n=36 экспериментальная группа; n=36 контрольная группа). Качественный этап состоял из онлайн-опроса 15 практикующих учителей химии, проанализированного методом тематического анализа.

Результаты показали, что учебные достижения экспериментальной группы были значительно выше, чем у контрольной: $U = 306$, $p < .001$, $r = .529$. Точность по итоговому тесту составила 81,9% в экспериментальной группе и 60,8% в контрольной. Качественные данные позволили выявить четыре темы: визуализация данных в реальном времени как ключевая педагогическая ценность IoT; органическая совместимость биогумуса и смарт-технологий; структурные барьеры для внедрения; а также рекомендация начинать с малого.

Данное исследование предоставляет эмпирические данные из контекста, недостаточно представленного в международной научной литературе, и предлагает воспроизводимую дидактическую модель преподавания устойчивой химии с использованием технологий.

Ключевые слова: *смарт-технологии, IoT, устойчивая химия, производство биогумуса, образование в области зелёной химии, Казахстан*

INTRODUCTION

The discipline of chemistry education is now at a crossroads. On one side, there is the decades-long tradition of teaching chemistry as a body of established knowledge: reactions to be mastered, mechanisms to be memorized, and calculations to be done properly. Simultaneously, more people are realizing that this tradition, while thorough, has not prepared graduates to see chemistry as the twenty-first century sees it. Today, when it comes to chemistry, it must be evaluated that chemistry must be environmentally responsible, socially useful, and a sustainable practice of science. For a long time now, these two orientations have existed uneasily in chemistry classrooms.

In addition, a process of transformation is underway. Rapid uptake of digital technologies-sensors, simulation platforms, adaptive learning systems, virtual laboratories, and real-time data tools in classroom and learning environments-has outpaced policy research that can inform their prudent use. Teachers are being requested to incorporate tools that they were never trained to implement into curricula that were never designed to incorporate these new tools to generate learning outcomes that existing assessment can never measure. The interest in "smart education" is real and in many ways justified. The question of "smart education" in the chemistry classroom is somewhat confusing, as it is about the technologies being introduced doing the pedagogical work proponents claim.

The convergence of the two transformations is occupied by this research. This article discusses the integration of smart technologies into sustainable chemistry teaching, focusing on the production of biohumus as a setting for this process. The chosen context does not vary at random. Biohumus may be defined as an organic fertilizer with the nutrients obtained through a chemically complex and locally important process. It demonstrates the practical application of green chemistry principles over a period of time as opposed to textbook examples. This process includes the biochemistry of organic materials decomposition, the soil science of nutrient recycling, the environmental chemistry of waste recycling, and the practical chemistry to keep living biological systems in optimum conditions. In the town of Kaskelen,

organic waste makes up 60% of municipal waste. However, the public is not very aware of alternatives such as biohumus (Abilbek et al., 2025).

There has not yet been systematic investigation which inquires whether smart technologies do have any effect on the teaching of this content and, if so, how and why. This study bridges that void or gap.

Background of the Study

Over the past twenty years, there has been a strong and repeated argument for sustainability to be taught in chemistry. The twelve principles of green chemistry established by Anastas and Warner (1998) laid the foundation. The UN Sustainable Development Goals, which were accepted in 2015, gave this framework worldwide policy legitimacy. Publications from IUPAC and the American Chemical Society following the Royal Society of Chemistry Green Shoots report (2021) have made calls for systemic curricular change. By 2022, a Nature editorial was commenting that nations might say good things about education in sustainable chemistry, but that has not resulted in any changes in the classroom events cited in (Mahaffy et al., 2023).

It is not primarily a question of will that there is a gap between aspiration and practice. The studies conducted by Nahlik et al. (2023) and Etzkorn and Ferguson (2023) reveal the real problems. These are that teachers are not properly prepared, schools have restrictions on curriculum design, and testing systems are unsuitable. The latter refers to the fact that they don’t reward the kind of systems thinking green chemistry needs. In addition, there is still insufficient pedagogical knowledge on sustainable chemistry. This is the knowledge of how to teach it rather than just what it is. To put it differently, the problem has more to do with eaching than with philosophy; and with institutions than with people.

The provision of the solution undertaken through smart technologies has a real reason to believe so. Sensor-based systems based on IoT have the capability of delivering information about chemical processes in real time. The processes generating such information would be expensive to test out with analytical equipment or invisible to students altogether. Through the use of virtual and augmented reality tools,

visualization of molecular phenomena is possible, which otherwise cannot be faithfully represented through physical drawings and diagrams. AI-based platforms may be capable of rendering feedback at a scale and in a detail that no human teacher can match. Yang et al. (2025), in a review of fifty-five empirical studies, found that smart technology improves teaching and learning when it is essentially integrated into a pedagogical system rather than just adding to teaching and learning practices.

The important caveat is that the tools are only effective "when they're integrated into coherent pedagogical systems." In their study with German secondary school chemistry teachers, Wohlfart et al. (2023) found a disconnect between how much teachers said they valued digital tools, and how much they were actually used in the classroom. The authors conclude that the integration of technology in chemistry education fails not because the tools aren't good enough, but because three things are often missing: proper teacher training, thoughtful curriculum design, and institutional support. In the Kazakhstani educational context, this finding is significant, especially since the strong tradition of chemistry teaching has been one of content knowledge but less so of inquiry-based, technology-rich, or sustainability-oriented pedagogics. Already research carried out in the very Department of Pedagogy of Natural Sciences of SDU University has started to empirically frame the gap in the specific local context. Research conducted by Abilbek et al. (2025) on AI-aided biohumus in Kaskelen reveals that during a month-long period, the IoT data collected from the live biohumus production process become too complicated to be predicted by a single environmental element. Rather, its development occurs through the simultaneous interaction of several parameters. Another field experiment by Abilbek et al. (manuscript submitted for publication) shows that with biohumus treatment, agrochemical properties and crop production in soil were found to show significant improvements at an experimental site at SDU University. This agrochemical evidence base makes biohumus a realistic and substantial subject of a chemistry curriculum. Such studies on their own do not provide an answer to the pedagogical question. They show that the subject matter exists and that the technological tools are efficient. The key question of education they leave

unanswered is: can these tools be used to teach biohumus chemistry to help learners comprehend sustainable chemistry more?

Purpose of the Study

The current research focuses on the application of smart technologies in teaching sustainable chemistry using biohumus production as the main content. The approach taken by the author is not in general terms of "technology in education," a framing that has produced a ton of research and very little practical guidance. It is a specific combination of content, technology, and instructional context. The objective is to learn about how and to what extent the inclusion of smart monitoring tools in a biohumus-based chemistry curriculum influences what students learn, how they engage with chemical concepts, and what types of understanding they develop of the principles of green and sustainable chemistry.

The work takes place at SDU University, Kaskelen, Kazakhstan - a location which represents a combination study of an international institution with a developing national tradition of teaching chemistry in technology-supported, sustainability-related ways, yielding a site that is simultaneously a hard and a live testing ground - the challenges here are real, the implications are practical, and the findings are likely to be interesting for dev institutions all over central Asia and further out.

Research Questions

The study is formulated based on three research questions, each of which addresses each of the three dimensions of the general study separately, yet alike.

Research Question 1: How does the integration of smart technologies enhance the effectiveness of teaching sustainable chemistry?

Research Question 2: To what extent do digital tools and interactive learning methods improve students' comprehension of the biohumus production process?

Research Question 3: Which smart technologies are most effective in fostering sustainable knowledge and skills in the field of green chemistry?

Significance of the Study

The literature will be enhanced by this study in three ways. It addresses a gap at the intersection of two active areas of research, namely smart education and green chemistry pedagogy, which so far have not entered into systematic empirical contact with each other. The review of the existing literature would indicate that both fields are mature and productive in their own right but that the intersection remains largely untraversed.

Second, it offers evidence from a Central Asian educational setting that is heavily under-represented in the international literature on technology-enhanced chemistry education. The difficulties and possibilities experienced in developing and running sustainable chemistry education at a Kazakhstani university are not merely a deferred version of what has been written of Western Europe and East Asia. Every system has a specific shape, determined by a unique educational history, institutional infrastructure, and policy environment. The originality of the study conducted herein is its ability to speak to those specificities in a way that external literature cannot.

Finally, the research contributes knowledge on pedagogy, specifically knowledge about design - not just whether smart technologies "work" in sustainable chemistry education, but what sorts of dependencies determine whether and how they "work". This sort of conditional knowledge is the sort that practitioners actually need, but curiously it is almost always the sort of knowledge that the research literature produces the least of.

The importance of this work is substantiated at the world level. In Bali, Indonesia, the International Conference on Education (ICEDU 2026) took place on 26–28 March 2026. A paper based on the preliminary findings of this study-*"Smart Technologies in Sustainable Chemistry Education: Biohumus Production"* (Abdybekova and Abilbek, 2026)-was presented there. The presentation generated substantial feedback from the evaluation panel and international participants. Members of the jury made suggestions concerning the widening of the sample of participants, the qualitative enrichment of the study, and its comparative international extension. It

should be noted that Dr. Wiets Botes of Sol Plaatje University, South Africa, expressed interest in collaborating to embed the findings from Kazakhstan in a cross-national research approach. As indicated above, these recommendations have contributed to the design and extent of the current dissertation. Also, the proposed collaboration with Dr. Botes is a suggestion for further investigation that was mentioned in Chapter 6.

Structure of the Thesis

The IMRAD format is the structure on which the thesis is based. It consists of six chapters. Chapter 1 provides the justification for conducting the research, states the research question, and signifies the research topic. Chapter 2 reviews the existing literature based upon the following five strands that cover sustainable chemistry education, the use of technology in teaching, and the outcome of learning through technology. In addition to sustainable chemistry education, how biohumus has been dealt with in Chapter 2 and what knowledge gap this thesis aims to fill.

The rationale for the selection of a mixed-method approach, participant selection, instrumentation, and intervention is delineated in Chapter 3. Chapter 4 (Results) explains the findings from two phases: the results of the quantitative pretest/posttest design and the thematic analysis of teacher survey data. Chapter 5 (Discussion) will discuss the findings about the research questions and literature. Chapter 6 (Conclusion) presents a summary of the theory, implications, limitations, and further research.

LITERATURE REVIEW

1.1 Sustainable Chemistry Education: Concepts and Global Trends

1.1.1 From Traditional Chemistry to a Sustainable Paradigm

At its core, chemistry investigates the process of transforming one substance into another. The focus is on turning raw materials into finished products and identifying unknown compounds to understand their molecular structure. Throughout the majority of the twentieth century, the transformation was hailed as a technical one, evaluated in terms of yield, purity, and efficiency. The downstream impacts on the environment and the health of workers were rarely tackled by the curriculum. Historians of science later observed that there was nothing surprising about these consequences, just that people chose not to ask.

Selective attention became very costly by the 1990s and could no longer be ignored. Pressure from legislation in the United States, particularly the Pollution Prevention Act of 1990, prompted chemists to begin thinking of waste not as an inevitable by-product of production, but rather as a product-design failure. It was within those regulatory and intellectual contexts that Paul Anastas and John Warner articulated the twelve principles of Green Chemistry in 1998. As a framework, the twelve principles relocated the ethical issues of chemistry from the end of the production chain to the start. The principles from atom economy and the use of renewable feedstocks to designing for degradation and minimizing side-products did not suggest a new branch of chemistry. The authors put forth a novel standard about quality chemistry.

The shift from industrial principle to educational philosophy is still taking place and is incomplete. Celestino (2023) observed a key difference, noting that traditional chemistry education is disciplinary and self-referential, as it teaches students to learn chemistry for its own sake.

Green and Sustainable Chemistry (GSC), by contrast, asks students to consider things at the molecular level and the systems level at the same time-not just 'Does this reaction work?' but 'Does this reaction belong?' which is a more difficult question to

teach and a more difficult one to assess. The syllabus update alone is not sufficient, say Karpudewan and Ahmad (2026). In other words, there is a need to rethink the whole teacher-content-student relationship: what is a chemistry class actually for?

1.1.2 Green Chemistry and the Architecture of Sustainable Curricula

The implementation of the UN Sustainable Development Goals in 2015 provided chemistry teachers with an unambiguous, publicly recognized reason for change. The three Sustainable Development Goals-SDG 4 (Quality Education), SDG 12 (Responsible Consumption and Production), and SDG 13 (Climate Action)-link the chemistry classroom to the real world. Curriculum designers from conservative institutions found this shift very useful, as it converted green chemistry from an ideological choice into an official policy requirement.

Simply aligning to policy goals does not translate into better teaching. According to Mahaffy et al. (2023), although a vast majority claimed to support curricular reform, in practice the change has been very slow in chemistry. According to the Royal Society of Chemistry's Green Shoots report (2021), sustainable chemistry should not be an additional topic, it needs to be integrated. The entire chemistry education framework, beginning with school level stoichiometry and moving on to organic synthesis in universities, must absorb this. According to Etzkorn and Ferguson (2023), status quo bias at nearly every level impedes this sort of structural change

The number of contact hours is predetermined. Assessment rubrics help you remember what you know. Most faculty have insufficient time to develop new curricula, and teacher preparation programs have fallen behind. Consequently, the same pattern plays out in many countries of the world: teachers who care about sustainability are stuck navigating a non-supportive system. We now return to the underlying problem of what teachers themselves know and what they are prepared to teach.

1.1.3 Pedagogical Content Knowledge and the Challenge of Teaching GSC

Lee Shulman, PCK (Pedagogical Content Knowledge) is a concept that was first presented by him in 1986. Upon reading this, it may be easy to forget a difference

between knowing and knowing how to teach it. The bridge between the two is not formed merely by adding further subject knowledge. A chemist who understands reaction mechanisms can be unable to explain them easily to a student who does not yet understand the mole concept. PCK is the bridge between the two. Importantly, it involves knowing how to represent specific content (which analogy works, which misconceptions to look for, and the order of ideas that ensures students can actually learn).

The PCK issue becomes more complex with Green and Sustainable Chemistry (GSC). In a study of secondary and pre-secondary school teachers across various school settings, Nahlik et al. (2023) found that the main obstacle was rarely a lack of enthusiasm or subject knowledge. Most teachers seem to understand the key concepts of green chemistry. Rather, the teachers did not seem entirely sure how to turn those principles into practical classroom tasks; for instance, planning a lesson on atom economy without it feeling too abstract, or making hazard reduction tangible for students who have never been in a lab. The instructional strategies for GSC are still being finalized.

The present study seeks to do exactly that. The incorporation of biohumus production as a chemistry topic is not simply the addition of yet another example to the list. The process of biohumus combines the disciplines of microbial biochemistry, soil chemistry, organic decomposition kinetics, and ecological feedback loops for a tangible result. This serves to make it precisely the kind of activity that can connect an abstract green chemistry principle to something students can actually see and measure at school.

1.1.4 Policy Contexts: Global Frameworks and the Kazakhstani Situation

Augmented responses to sustainability challenges in chemistry education within an institutional framework were observed during 2020-2024 in different parts of the world. The coordination between technology, education and sustainable development is the work of UNESCO. The 2022 Recommendation on the Ethics on Artificial Intelligence has made it clear that responsible use of technology for education as an

integral part of education for sustainable development (UNESCO,2022). Consequently, IUPAC called on national chemical bodies to harmonise their curricula and develop chemical education to green chemistry. The American Chemical Society Green Chemistry Institute developed modular materials to be immediately incorporable into existing general and organic chemistry courses (Etzkorn & Ferguson, 2023). Because a fully serviceable redesign was unlikely, smaller, compatible choices were put together for scientists wanting to require a green chemistry component.

Kazakhstan serves as a pertinent case in point. The chemistry education system of the country has been built upon the Soviet model, which has a strong emphasis on quantitative problem-solving and theoretical knowledge, and much less on inquiry, environmental thinking, and real-world applications. The new national curriculum was introduced in 2019, which set competency-based standards that include environmental literacy. In addition, the State Program for Education Development 2020–2025 has set the targets for digitalization of teaching at all levels. These changes appear significant on paper.

In practice, the gap between policy and reality is readily apparent in sustainable waste management, which directly links to the field of chemistry education. In Kazakhstan, organic waste accounts for an estimated 60% of municipal solid waste in the country, which still does not have the capacity to handle this type of waste.

1.2 Smart Technologies in Education: A Framework for Chemistry Teaching

1.2.1 What "Smart" Actually Means in an Educational Context

There are many things in education which are called “smart” but which aren’t all that smart. Interactive projectors that are merely smart boards, or campuses designating themselves as 'smart' because they boast a mobile app for room booking. This term is now used for any classroom with a screen, making it difficult to discuss when exactly the concept applies and when it does not.

An alternative guiding definition of smart comes from Zhu et al. (2016): “According to our study, this is a smart learning environment composed of smart environments,

smart pedagogy, and smart learners. ‘Smart’ here indicates the system formed by these three components, rather than a single hardware/software package. In effect, a smart learning environment is responsive to learners and connects what students are reading in the classroom to the real world, while eliciting this kind of thinking that a textbook cannot do alone”, a lower overarching definition of smart environment calls back the idea. Yang et al. (2025) built on this understanding by conducting a bibliometric review of Fifty-five empirical studies on smart learning environments and smart learning, and identified five interdependent pillars: intelligent technology, smart pedagogy, smart learning environments, smart learning, and smart learners” (p. 237). A system that relies on using things like IoT, artificial intelligence, virtual reality, big data analytics and cloud computing in concert as one system instead of separate non-integrated tools, and so on, that may or may not be smart in this sense.

It is of utmost importance for chemistry education in particular. A chemistry teacher does not create a smart learning environment just by adding a YouTube video to a lecture. However, it is a different undertaking entirely when a teacher has their students using real-time gas sensors to monitor a decomposition reaction, analyzing this data on a shared cloud platform, and receiving auto-generated feedback on their interpretations. The technology engages in pedagogical tasks rather than simply presentation work. Therefore, it is relevant for the teaching of sustainable chemistry.

1.2.2 The Internet of Things and Real-Time Data in Science Learning

The Internet of Things (IoT) as an educational idea refers to networks of connected devices and sensors that collect and share live data about physical processes. In industrial or agricultural sites, IoT systems constantly monitor the temperature gradient, chemical concentration, and moisture content. In a classroom context, this same principle provides a thing which chemistry teachers have forever struggled to deliver: real live data from real processes, which students set up and interpret themselves.

The epistemic value of this is more important than the motivational one, although it can indeed increase motivation significantly. Chemistry students often treat

measurement and data as a sort of rite of passage, weighing ingredients, writing numbers, and calculating results that confirm what the textbook said would happen. When the data is from a live system, which may behave erratically, students tend to connect observation to understanding in a completely different manner. The learning outcomes improved through IoT reported Abichandani et al. (2022) and Ghashim and Arshad (2023). According to Ghashim and Arshad (2023), 96% of teachers reported that student engagement increased as the IoT helps in personalizing each student's learning and improving understanding. Mylonas et al. (2023) conducted a follow-up study and discovered that IoT-enabled environments are particularly powerful in achieving sustainability skills because students can monitor resource use and environmental parameters in real time rather than reading about them.

Abilbek et al. (2025) made direct monitoring of biohumus for thirty days in practice. Youngsters equipped with linked sensors exhibited stronger soil chemistry learning outcomes than those without. Rather than viewing NPK ratios just as numbers from the textbook, they began observing such values every day as they constantly varied with microbial activity. When local sustainability projects contain IoT tools, they convert raw data into a living teaching instrument. They create a bridge between digital instruments and chemistry systems and processes presently ongoing within environmental settings.

1.2.3 Virtual and Augmented Reality: Between Visualization and Genuine Learning

The introduction of virtual reality in chemistry education came with a great deal of promise, and it has delivered on some of these promises. The rationale for VR in chemistry is simple: molecules are not visible, reactions happen at scales that cannot be observed directly, and laboratory procedures often carry hazards that cannot easily be arranged for student experimentation. If a VR environment is designed perfectly, it could turn molecular geometry into a tangible experience, help students manipulate 3D structures, and undertake experiments that are not doable or are dangerous in a real lab. These are effective benefits and not a marketing gimmick.

However, it turns out the science is more complicated than what we got excited about. Workneh and Estifanos (2024) conducted a quasi-experimental study for a full semester with undergraduate chemistry students. According to Bazie et al. (2024), students in virtual labs performed equally well as students in real labs (mean differences: 7.12 points, $p = .07$), and did much better than students who received only lectures in both groups. This indicates that an alternative to physical labs can be used in case physical labs are not available. When resources are scarce, this efficiency edge matters. Tan et al. (2024) compared augmented reality (AR) vs. virtual reality (VR) in higher education chemistry and found that both technologies have significant impacts on knowledge acquisition as well as motivation. According to Lam et al. (2024), augmented reality (AR) outperformed virtual reality (VR) by 44% as the former generated higher post-test scores as well as student satisfaction.

This is especially relevant for such sustainability topics as biohumus production. That's because biohumus production has two dimensions. One is the physical visible part. In this case, organic decomposition. Another is the chemical changes which are happening during the process but are invisible. Another point to mention is that the VR setup cost can be very expensive for many institutions which would make the AR solutions or mobile-based applications much more practical for usage in a classroom.

1.2.4 AI-Driven Adaptive Learning and Personalized Instruction

Artificial intelligence (AI) first made its way into edtech through adaptive learning technology platforms that constantly assess how students are responding, identify their gaps and misconceptions, and adjust the pace and sequence of content delivery accordingly. Almasri (2024) engaged in a systematic review of 74 empirical studies published between 2014 and 2023. Broadly, the findings indicate a positive impact of AI on science learning outcomes. These benefits comprise an improved learning environment, automated assessment, and performance prediction. The assessment was also able to identify some issues which appeared regularly. The bulk of the studies that were scrutinized were short-term ones in which research was done

in controlled settings that do not reflect the complexities of real classrooms. Also, the most frequently mentioned risks concerned ethics, data privacy, and algorithmic bias.

The most practical applications in chemistry education in particular have less to do with fully automated instruction and more to do with providing specific feedback at the scale that a single teacher cannot physically provide. According to Sagynbayeva et al., the integration of ICT tools into chemistry education in Kazakhstan boosts students' knowledge (2022).

1.2.5 The Digital Tools Debate: Added Value or Modern Gimmicks?

Not everyone agrees that all of this use of technology is a good thing for learning though. Wohlfart et al (2023) interviewed secondary school chemistry teachers and found, with a title that reflects their frustration, a "general optimism bias" in how positively teachers talked about the role of digital tools in teaching vs. how rarely they used them in practice. Teachers who valued VR and molecular simulation software often cited lack of time, insufficient training, and not knowing whether these tools really offered more than "what could be done already".

This corrective rectifies the excessively enthusiastic literature previously seen. Technology adoption in education has less to do with the quality of the tools than the conditions teachers work in. The effective integration of digital tools in chemistry education requires effective tools, as well as systemic and pedagogical changes to teachers, curriculum, and institutions. This restates the structural argument from Chapter 1 concerning green chemistry pedagogical reform. Both challenges have a similar shape.

According to the literature, smart technologies can be useful in chemistry education if they are used to do something complex. This includes making the invisible visible, obtaining real data from real processes, and giving feedback to a scale no human teacher could ever hope to. Their efficacy is at the lowest when they approximate, but with a higher cost and greater complexity, what a good teacher with a whiteboard and some laboratory equipment can already do. The standards are what the study itself will apply when it assesses those technologies.

1.3 Impact of Smart Technologies on Student Learning Outcomes in Chemistry

1.3.1 What "Learning Outcomes" Actually Means in This Context

Before looking at what research says, it helps to be clear about what the term learning outcomes actually covers in chemistry education, as it covers a wider range of things than it might appear. The most basic answer to what student outcomes would be is that it is what students know and can do after they have been instructed, including the content knowledge they retained, the procedures they can perform, and the concepts they can apply to unfamiliar situations.

New research in chemistry education does not confirm that having content knowledge and procedural skills alone guarantees complete learning. Student engagement, defined as being actively attentive, investing effort, and perceiving the task as meaningful, is a strong predictor of developing deeper conceptual understanding (Schindler et al., 2017, as cited in Godsk & Møller, 2024). Moreover, motivation determines the encoding and transfer of chemical knowledge. There is an important difference between students with mastery orientation, who wish to understand the science behind phenomena, and students with performance orientation, who wish only to pass the tests. Although skills such as critical thinking, systems thinking, and engaging with data are all considered important in modern science education, the evidence behind the success of each can vary in strength.

1.3.2 Comparative Evidence: Smart vs. Traditional Instruction

The most notable design employed in technology-enhanced learning studies is the comparative design. One group receives instruction that incorporates a smart technology, the other receives “ordinary” instruction, and they are compared on pre- and post-measures. The added-value methodology provides a straightforward way to demonstrate technology’s added-value. However, such studies frequently ignore the contextual factors that influence what any pedagogical approach actually achieves.

These findings are consistent across various educational contexts. As an illustration, a study conducted by Bazie et al. (2024), who investigated undergraduate

chemistry students at Dilla University via a quasi-experiment, found that the use of virtual laboratories produced learning gains that are not statistically different ($p = 0.07$) from those of students who received hands-on laboratory learning. Importantly, students who experienced active learning performed better than those who only received lectures.

This is especially important for green and sustainable chemistry. It can be seen that the chemistry of biohumus production can be analyzed using digital tools, while the practical administration of a vermicomposting system cannot be adequately simulated through electronic means. Instead of replacing the hands-on lab process, the smart technology makes it more intelligible for the students by establishing a connection between 'real-time' environmental data and the basic chemical principles behind them.

1.3.3 Student Engagement and Motivation: What the Evidence Shows

According to multiple studies (Godsk & Møller, 2024), digital tools that engage students in active use achieve higher engagement than classroom instruction. For instance, Crocodile Chemistry simulation software for undergraduate students resulted in significantly higher post-test scores (Alqallaf et al., 2025). The largest gains were not in recall of procedures but in conceptual understanding. This type of pattern occurs often in chemistry education research.

Understanding student engagement gets complicated by the factor of novelty. Assessments of engagement that are done immediately after the deployment of any technology tend to capture short-term engagement rather than lasting changes in motivation. Longitudinal research tends to document less extreme effects (Miguel-Alonso et al., 2023). When the period under study was made sufficiently long (i.e., over an extended period), many reported perceived usefulness and ease of use are potential determinants of students' sustained engagement with smart platforms (Godsk & Møller, 2024). Within environments where digital infrastructure is limited, this is crucial.

1.3.4 Critical Thinking and Systems Reasoning in Technology-Enhanced Chemistry Learning

A recent study shows that technology in collaborative inquiry influences higher-order thinking. According to a systematic review by Chen & Chen (2024), technology-enabled collaborative inquiry achieved greater gains in critical thinking and scientific reasoning than traditional instruction. According to the findings, students who had little previous understanding received a strong benefit, which implies that technology can help to close achievement gaps.

Furthermore, three-dimensional molecular structure simulation tools improved the chemistry competence of students according to Hoai et al (2023). The most significant improvements were located in spatial reasoning and molecular geometry.

1.3.5 Teacher Readiness and the Conditions for Effective Technology Integration

The most consistent finding in the literature emphasizes teacher preparation rather than immediate student outcomes. Current data indicates that the success of any technology depends largely on whether educators grasp its underlying pedagogical purpose, and if they receive adequate support within a coherent learning sequence. This aligns with an investigation by Wohlfart et al. (2023) into secondary school chemistry instructors, which demonstrated that technology integration frequently falters not due to defective tools per se, but because critical components—namely targeted professional development, intentional syllabus design, alongside systemic institutional backing—are missing.

This issue is closely linked to the overall goal of the current research. There is no guarantee that a 30-day biohumus data sensor network will automatically be a teaching tool. Only when a teacher has the specific PCK to transform that raw data into learning activities does it become one. In the end, the smart chemistry classroom is not so much about the digital instrumentation per se, but the teacher's preparedness to help students with the complex, real-world science that it reveals.

1.4 Biohumus as a Subject of Sustainable Chemistry

1.4.1 Why Biohumus Belongs in a Chemistry Classroom

Soil science in chemistry education is being treated as somebody else's domain: either biology teachers or agricultural and environmental studies departments. This method is incorrect, and it has significant costs, pedagogically speaking. The biohumus production and properties contain much of chemistry. To understand the contribution of biohumus to a change in soil fertility, it is necessary to consider nitrogen mineralization and phosphorus solubilization, as well as the role of humic and fulvic acids as chelating agents. It is necessary to apply pH, electrical conductivity, moisture equilibria, and oxidation-reduction chemistry to a living system in order to monitor a composting process.

Producing biohumus is not merely a useful example that chemistry teachers can take out of their bag of tricks from time to time in class. Biohumus production is pedagogically unique. It makes evident in one integrated process the connections between molecular chemistry, soil biochemistry, and environmental sustainability that green chemistry education seeks to establish.

1.4.2 The Biochemistry of Biohumus: What Students Are Actually Learning

At its core, biohumus production relies on biochemical transformations driven by earthworms working alongside microbial communities. Students can track, manipulate, and ultimately make sense of these underlying chemical parameters in real time. Grasping this dynamic requires looking at several distinct yet overlapping pathways.

To begin with, the earthworms would physically break down the organic wastes. This would further increase the surface area available for microbial attack. Secondly, the humification process is the coalescence of unstable organic matter into stable humic substances through fungal and bacterial enzymes. The third important process in soil nutrient movement and transformation is of organic nitrogen, phosphorus, and potassium into inorganic forms that are available to plants (NH^{4+}, NO^{3-}, H_2PO^{4-}).The ability of humic substances to bond metal ions aids in improving the soil retention

capacity. Ensuring that both chemical and physical conditions operate smoothly is the objective. Moisture levels should range between 60% and 80%. The carbon-to-nitrogen ratio must be balanced. The temperature must also be controlled. This gives the students an idea about biochemical balance and process control.

1.4.3 Agrochemical Effects: Evidence from the SDU University Field Study

Abilbek et al. (manuscript submitted to publication) conducted a field experiment on biohumus use in agrochemicals in the soil and eggplant (*Solanum melongena* L.) and pepper (*Capsicum annuum* L.) yield study in the open field at the SDU University experimental site Kaskelen in 2025. The study was conducted using a randomized complete block design having six treatments and three replications. Soil samples were drawn on three occasions that is before sowing in April, mid-season in July and post-harvest October.

Mid-season data indicated the agrochemical processes through which biohumus improves the nutrition of crops. Compared to the mineral-only control, the investigations found plots fertilized with biohumus had 10–18% more available nitrogen and phosphorus and 7–12% more exchangeable potassium. According to the authors, organic materials and humic substances in biohumus decompose slowly and therefore supply nutrients more evenly during periods of intense growth than mineral fertilizers alone do. Nutrient uptake and irrigation-induced leaching of the control plots caused a loss of 15–20% available NPK by the end-season. Biohumus-treated soils experienced no change in pH (6.6 to 7.2), and electrical conductivity remained optimal throughout the season—something a textbook description alone cannot show.

The findings of the yield results were in line with the data from the agrochemical analysis. The yield of the plants biohumus-treated was 22-27 % higher for eggplant and 18-23 % greater for pepper compared to the mineral-only treatment. The best application rate was 1.5 t/ha. An increase in yield did not occur when the rate was raised to 3.0 t/ha. This indicates there is a saturation point of nutrients, beyond which influx of nutrients does not increase nitrogen uptake or crop growth.

This dose-response relationship provides a valuable teaching lesson by itself, showing that soil chemistry behaves as a dynamic, non-linear system.

1.4.4 Biohumus as Circular Economy Chemistry

Biohumus production embodies a direct manifestation of green chemistry, specifically focusing on waste prevention. This process diverts organic materials destined for landfills-ranging from kitchen scraps to agricultural residues and plant matter-into a highly beneficial cycle. The resulting nutrient-rich soil amendment effectively replaces synthetic fertilizers, which demand significant energy expenditure during manufacturing. Crucially, the entire cycle avoids hazardous inputs, generates zero toxic by-products, and delivers a final agent that actively restores rather than impairs the existing soil ecology.

The urgency of this logic of the circular economy is particularly acute in Kazakhstan. According to Abilbek et al. (2025), organic waste represents roughly 60% of municipal solid waste in cities like Kaskelen, but current treatment infrastructure is insufficient. These organic matters, which now produce methane in landfills, could instead serve as valuable feedstock for biohumus production. This will not only help to solve the waste management problem but also help to convert waste into soil and reverse the problem of soil depletion in the region. The model under consideration has potential as well as challenges when it comes to scaling, according to studies. Micro-enterprises' production and direct sale of biohumus to local farmers provide substantial net profit margins at low capital requirements (Thirunavukkarasu et al., 2022). Nonetheless, social and institutional barriers still represent significant limitations, including low public awareness, poor sorting of green waste, and a lack of supportive policies.

1.4.5 Biohumus Production as a Pedagogical Object: What Makes It Distinctive

The claim that biohumus is an educational symbol of sustainability in chemistry education rests upon a number of distinct pedagogical characteristics that make biohumus special among other examples that can be taught in this subject area.

Firstly, it means something to local people. The management of organic waste is a visible, unresolved issue in Kaskelen and in most other similar communities in Kazakhstan and Central Asia. Students shouldn't be burdened with worrying about an abstract environmental problem that connects with their neighbourhoods. Such localization goes a long way in enhancing student motivation in the teaching of environmental science, as students are able to trace a line between what they learn and the actual intervention (Karpudewan & Ahmad, 2026).

Moreover, it is time-consuming. Most chemistry experiments take from one hour to three hours to complete. Biohumus production occurs over thirty to sixty days, and students are expected to witness a process, not conduct a procedure. The organizational setup permits the formation of scientific practices involving systematic observations, interpretations of data over a long time, and manipulation of variables that cannot be formed in short experiments. A study by Abilbek et al. (2025), which visually tracked the biohumus process in real-time over thirty days, suggested that soil fertility essentially involves a non-linear relationship between a large number of interacting variables—one that should only be appreciated by students who are able to access the full time series of data.

Third, it is really open-ended. Producing biohumus cannot guarantee success. An increase in temperature could kill earthworms. If feedstocks are added in the wrong proportion, the conditions will turn anaerobic. Inclusion of nitrogen can drop pH and inhibit microbes growth. Not teaching issues, but teaching possibilities. A student who troubleshoots the reason for the composting system which is not yielding quality biohumus and manages the conditions to get it right is doing chemistry and not only following the instructions.

1.5 Integrating Smart Technologies and Sustainable Chemistry: Research Gaps and the Case for This Study

1.5.1 Project-Based Learning as the Natural Meeting Point

The foregoing begs the important question that remains unanswered in literature, which is how smart technologies, sustainable chemistry content, and authentic student

learning can take place in the same classroom. Previous research has examined these three elements, but usually not together.

PBL can be the most natural way of instruction that binds them together. The more rigorous applications of PBL suggest designing the learning experience based around an extended, real, open-ended problem that students investigate over time, where the methods and concepts of the field become useful tools in authentic inquiry (Vergara-Castañeda et al., 2021). According to Lestari et al. (2024), the bibliometric analysis of 319 studies on PBL in chemistry education published between 2014-2024 revealed that effective implementations share three aspects, namely: they are based on real local or community problems; students are allowed enough time to develop real expertise; and there are explicit processes of reflection connecting project work to core disciplinary concepts.

These characteristics are provided by biohumus production. Provided the subject matter is described clearly so that the underlying chemical connections are made explicit, it can be tracked with the aid of smart technologies over a period of weeks. The Da Vinci Project at Utrecht University is a most useful example of this framework, as it has been conducting transdisciplinary challenge-based learning in the undergraduate chemistry curriculum over five years (Sluijs et al., 2024).

1.5.2 Smart Monitoring in Agricultural and Environmental Learning Contexts

The use of IoT monitoring tools in educational programmes with living biological systems has been included quite recently in the education field, with little research to draw upon. The majority of existing research of IoT in education has focused on smart classroom environments regarding attendance tracking, environmental sensors, and student engagement monitoring. Using IoT as an instrument for scientific inquiry that generates data about a process students are actively investigating is rather different.

The couple of studies which employ IoT in this more substantive way tend to yield findings which go beyond engagement effects. According to a study done by Abilbek et al. (2025), it was established that through continuous sensor data in IoT-

based real-time monitoring of the biohumus production process, it established interactions between temperature, aeration and microbial activity that would not be revealed by periodic manual sampling. This deep dataset yields a fundamentally different view of complex chemical systems compared to standard, disconnected testing.

SDU University's research actively applies these parameters directly within a practical classroom setting. The thirty-day IoT monitoring study by Abilbek et al. (2025) tracked six environmental parameters of an active biohumus process and applied machine learning analysis to the resulting dataset. Soil fertility showed near-zero linear correlation with any single variable. This suggests that soil fertility can only be understood as an emergent property of complex interaction. This type of finding shows why simple explanations are inadequate and makes a case for students to engage with real chemical complexity.

1.5.3 What the Literature Does Not Yet Know

When researchers are transparent about the gaps in their research, it does not simply become a formality by way of academia. Rather, this is how a study justifies its existence. The literature examined in the previous sections is rich and sophisticated, but it leaves a number of questions genuinely open.

This study concerns the first gap on the content, technology, and pedagogy that this study brings. A growing body of literature on PBL approaches in sustainable chemistry education, along with substantial literature on smart technologies in chemistry education. The production of biohumus is well documented in scientific literature. There is yet no empirical work investigating what happens to student learning when smart monitoring technologies are applied specifically to teach the sustainable chemistry of biohumus production in a real educational context over an extended time period. Until now, no research has combined these three active areas.

The second gap is contextual and geographical. The vast majority of research on smart education and green chemistry education has been done in Western Europe, East Asia, and North America. There is a lack of research on these issues in Central Asian

educational institutions. The local context plays a significant role; studies from Kazakhstan, including Abilbek et al. (2025), confirm this assertion. The international literature on the challenges faced in integrating smart technologies within chemistry education does not fully capture the institutional, cultural, and infrastructural context. According to Sagynbayeva et al. (2022), national digitalization priorities-namely, the Digital Kazakhstan programme-affect how ICT is understood and used in classrooms.

1.5.4 Summary and Justification for the Present Study

To date, the literature review has made several related claims. Educating students in green and sustainable chemistry is a genuine priority. However, preparing teachers to put that into practice requires pedagogical knowledge that is currently lacking in most teachers. Smart technologies possess real capabilities that can support the learning and teaching of chemistry; for example, the ability to provide authentic data from real processes and support extended inquiry. However, the educational value of these technologies will depend very much on how they are pedagogically integrated.

The evidence indicates that technology-enhanced chemistry education holds promise but can also be fragile since the same technology in the hands of different people yields different results. The process of biohumus manufacturing is one that is chemical rich and meaningful in the local, meaningful over time, and genuinely open-ended as it gives life to green chemistry principles that students can measure and take note. Field research undertaken at SDU University has shown both the agrochemical substance of this claim and its pedagogical potential.

It has not yet been shown - and is the goal of the present study - whether and how smart monitoring technologies can mediate the relationship between the chemical reactions in a biohumus production system and a student's developing understanding of sustainable chemistry. This question is not about whether IoT sensors make good data or whether biohumus is a good topic for a chemistry module. It is a question about learning: about what students actually come to understand when they set up a composting system, connect it to sensors, watch thirty days of pH and nitrogen data accumulate, try to explain what they see, find that their explanations do not quite work.

METHODOLOGY

2.1 Overview of the Research Design

This study aims to examine the educational impact of smart monitoring technology on the project-based chemistry teaching of sustainable biohumus production. The empirical effort seeks to answer three research questions.

The study uses a mixed-methods convergent parallel design (Creswell & Plano Clark, 2018). This approach involves collecting both quantitative and qualitative data within the same phase of a research project. The quantitative data evaluate changes in students' content knowledge, systems thinking, and motivation. The qualitative data provide evidence of how students learn, solve problems, and interact with technology in the classroom. Together, both sources supply empirical evidence and contextual understanding.

Mixed-methods designs are widely regarded as well-suited for chemistry education research, particularly when examining technology integration, since statistical changes in test scores seldom reveal why or how a technology has succeeded or failed.

2.2 Phase 1: Quantitative Study

2.2.1 Design

The first phase was quasi-experimental, testing two existing groups of students with pre-test and post-test measures. This design was selected because the university timetable made random assignment impossible; students were already enrolled in their respective course sections. Quasi-experimental approaches are appropriate when full experimental control is not possible, as they allow assessment of an educational intervention within an undisturbed classroom environment (Campbell & Stanley, 1963).

2.2.2 Participants

During the spring semester of the 2025–2026 academic year, 72 third-year undergraduate students enrolled in the Chemical Industry course at SDU University, Kaskelen, Kazakhstan, formed the study sample. The students were separated into two

groups:

- Experimental group: n = 36 (received IoT-integrated instruction)
- Control group: n = 36 (received conventional instruction)

All participants provided voluntary informed consent prior to the study. They were assured that their answers would not affect their grades. To safeguard anonymity, participants were assigned numerical codes. Both groups had undergone standard instruction in general chemistry but had no prior formal exposure to biohumus production, vermicomposting, or IoT-based environmental monitoring.

2.2.3 Instructional Intervention

The research took place over four 50-minute sessions during one month of the spring semester. The researcher (Azhar Abdybekova) and the course instructor (Ms. Assel Bizhanova) designed and delivered the lessons collaboratively to ensure alignment with the existing curriculum.

Both groups received the same content (biohumus production, green chemistry principles, and the role of environmental parameters in vermicomposting) across the same three lesson phases: lecture, video demonstration, and hands-on practical laboratory work. The only systematic difference between the groups was the measurement technology used in the practical component.

Experimental Group — IoT-Enhanced Instruction: Students used an Intelligent Soil Detector, a smart IoT sensor capable of measuring soil temperature, moisture content, and pH in real time, displaying results on a digital readout. Students recorded sensor readings from three prepared soil and biohumus containers, compared readings against optimal vermicomposting parameters, and completed a structured laboratory worksheet requiring chemical analysis and evidence-based reasoning.

Control Group — Conventional Instruction: Students performed the same laboratory tasks and worksheet using a standard thermometer for temperature and pH indicator strips for acidity. Although these tools are slower and less precise than the IoT sensor, the level of analytical reasoning required to complete the worksheet was identical for both groups.

2.2.4 Research Instruments

Pre-Test and Post-Test

A 10-item multiple-choice questionnaire was developed to assess students' knowledge of sustainable chemistry in the context of biohumus production. The assessment covered: green chemistry principles and waste valorisation; optimal biochemical parameters for biohumus (temperature, moisture, pH, C:N ratio); the function and advantages of IoT sensors in real-time chemical monitoring; and scenario-based reasoning requiring the identification of chemical problems and appropriate interventions.

Each item offered three response options, with one correct answer. The maximum possible score was 10. The pre-test and post-test contained the same questions; however, in the post-test, the order of the answer options was randomised to reduce the likelihood of students relying on memory rather than understanding, thereby ensuring that score improvements could be attributed to genuine learning gains (Field, 2018).

Before administration, the instruments were reviewed by the thesis supervisor and then submitted to a panel of five anonymous chemistry educators from various universities in Kazakhstan. Each expert independently rated all ten items on a five-point scale (1 = not relevant; 5 = highly relevant) for relevance, clarity, and appropriateness for third-year undergraduate students.

Laboratory Worksheet

Structured worksheets guided student inquiry across each practical session. Students took readings from three prepared containers, identified which container presented the most favourable biohumus conditions, diagnosed chemical imbalances in the others, and proposed evidence-based interventions grounded in green chemistry principles. The worksheet functioned as an instructional scaffold, actively supporting rather than replacing student reasoning.

Quick Reference Guide

Each student received a one-page reference guide summarising the key

parameters of biohumus production (ideal ranges for temperature, moisture, and pH; consequences of deviation; chemical remediation options). The guide was developed from the agrochemical literature and from findings of the SDU University field study (Abilbek et al., 2025).

2.2.5 Data Collection Procedure

Data collection for the quantitative phase took place across four 50-minute laboratory sessions during the spring semester of the 2025–2026 academic year at SDU University, Kaskelen, Kazakhstan.

The pre-test was administered to both groups at the beginning of the first session, prior to any instruction. Students completed the 10-item multiple-choice instrument independently under standard classroom conditions. No instructional materials were distributed before the pre-test to ensure that baseline scores reflected prior knowledge only. Completed answer sheets were collected immediately and assigned numerical codes to ensure anonymity.

The instructional intervention was then delivered across the remaining sessions as described in Section 2.2.3. Both groups received identical content through lecture, video demonstration, and hands-on laboratory work. The only systematic difference between the groups was the measurement technology used during the practical component: the experimental group used an Intelligent Soil Detector (IoT sensor), while the control group used conventional instruments (thermometer and pH strips).

The post-test was administered at the end of the final session, after the intervention was complete. The post-test contained the same ten items as the pre-test; however, the order of the answer options was randomised to reduce recall-based responding. Completed post-test sheets were collected and coded using the same numerical identifiers assigned during the pre-test administration, enabling matched pre-test and post-test scores to be linked for each participant.

All data were entered into a spreadsheet and subsequently imported into Jamovi (version 2.3) for statistical analysis. Gain scores (post-test minus pre-test) were calculated for each participant and used as the primary outcome measure in between-

group comparisons.

2.2.6 Data Analysis and Instrument Validity

Quantitative data were analysed using Jamovi (version 2.3). Prior to inferential analysis, normality was assessed for all groups using the Shapiro-Wilk test. Results indicated significant departures from normality in both pre-test and post-test scores across both groups: Experimental pre-test ($W = 0.905$, $p = .005$), Control pre-test ($W = 0.874$, $p < .001$), Experimental post-test ($W = 0.923$, $p = .015$), and Control post-test ($W = 0.900$, $p = .003$). Given these violations of the normality assumption, non-parametric tests were used throughout. Parametric tests (independent-samples t-test; paired t-test) require normally distributed data, interval-level measurement, and sufficiently large samples - none of which could be confirmed in this study. Non-parametric alternatives were therefore selected: the Wilcoxon Signed-Rank Test (in place of the paired t-test) and the Mann-Whitney U test (in place of the independent-samples t-test). These tests make no distributional assumptions and are appropriate for ordinal scores with small-to-moderate sample sizes.

The following analyses were conducted:

- A Mann-Whitney U test was used to assess baseline equivalence between groups using pre-test scores prior to the intervention.
- A Mann-Whitney U test on gain scores (post-test minus pre-test) was used to compare the differential learning gains between the experimental and control groups, directly addressing RQ1.
- A Wilcoxon Signed-Rank Test was applied to the experimental group to assess whether IoT-integrated instruction produced a significant within-group improvement from pre-test to post-test, directly addressing RQ2.
- The rank-biserial correlation coefficient (r) was used to calculate effect size, interpreted as small ($r = .10$), medium ($r = .30$), or large ($r = .50$) following Field (2018). The significance threshold was set at $\alpha = .05$.

The significance threshold was set at $\alpha = .05$. Full descriptive statistics and Shapiro-Wilk normality test results for both groups are provided in Appendix 7.

2.2.7. Content Validity of the Pre-Test and Post-Test

Prior to the main intervention, the pre-test and post-test instruments were submitted to a panel of four anonymous chemistry educators from various Kazakhstani universities for expert content validation. Each expert independently rated all fourteen items on a five-point scale (1 = not relevant; 5 = highly relevant). The overall expert rating was 4.34 out of 5.0, indicating strong content validity. Twelve of the fourteen items received mean ratings of 4.0 or above. Item 8, which concerned scenario-based reasoning, received the lowest mean rating (M = 2.25), suggesting it may be overly complex for the target level; this item was retained as it relates to a specific learning objective, and its relatively low rating is noted as a limitation.

Inter-rater agreement was assessed separately for the pre-test and post-test instruments using Kendall's Coefficient of Concordance. For the pre-test, $W = 0.900$ ($\chi^2 = 40.518$, $df = 9$, $p < .001$); for the post-test, $W = 0.873$ ($\chi^2 = 39.272$, $df = 9$, $p < .001$). Both values indicate very strong agreement among the five expert raters, confirming consistent and reliable evaluation of both instruments. These results, alongside the overall mean expert rating of 4.34 out of 5.0, confirm strong content validity for the instruments prior to administration. Full expert rating data and Kendall's W test results for the pre-test and post-test instruments are provided in Appendix 8 and Appendix 9 respectively.

2.3 Phase 2: Qualitative

2.3.1 Design

The qualitative phase consisted of an online expert survey with a semi-structured questionnaire composed of fourteen items in total, including thirteen multiple-choice questions and a final open-ended item. This method is sometimes referred to as an asynchronous written survey, which was chosen because it allowed participants time to think about their responses without needing to organize a specific meeting time (Meho, 2006). This practical approach enabled reaching participants from various institutions and different regions of Kazakhstan.

The qualitative data from the open-ended items in the survey were analyzed

using inductive thematic analysis, following the six-phase framework of Braun and Clarke (2006): familiarization, coding, theme generation, theme review, theme definition, and reporting. In essence, what this meant in practice was revisiting the written comments made by the teachers and lecturers multiple times, initially coding the various descriptions of the barriers faced in the classroom and coding these into broader themes about how local schools were ready for green technology.

2.3.2 Participants

Fifteen chemistry teachers were recruited via purposive sampling - the selection of participants who can best address the research questions rather than on the basis of statistical representativeness (Patton, 2002). Participants were practising chemistry teachers or university lecturers with at least some familiarity with or interest in using digital technologies in teaching.

The sample comprised eight school chemistry teachers, six university lecturers, and one educationalist. Ten participants (66.7%) had fewer than three years of teaching experience; four (26.7%) had three to ten years; and one (6.7%) had more than twenty years. Nine participants (60%) reported frequent use of digital or smart technologies in teaching; four (27%) reported occasional use. On average, participants rated their confidence in using these technologies at 4 out of 5, indicating a high level of self-reported proficiency.

Survey links were distributed via Google Forms to professional networks over the course of one week. Participation was voluntary and anonymous. Thematic saturation - the point at which further responses produced no additional distinct themes - was achieved within this sample of fifteen (Braun & Clarke, 2006).

Furthermore, the diverse background of the participants provided a multifaceted perspective on the integration of digital tools in chemistry education. This variation in teaching experience allowed for a more comprehensive understanding of potential barriers and facilitators in different educational settings. Consequently, the gathered qualitative data offers rich, contextual insights that enhance the overall credibility of the survey outcomes.

Table 2.1. Survey Participant Characteristics (n = 15)

Characteristic	Category	n	%
Position	School chemistry teacher	8	53.3%
	University lecturer / instructor	6	40.0%
	Other	1	6.7%
Teaching experience	Less than 3 years	10	66.7%
	3–10 years	4	26.7%
	More than 20 years	1	6.7%
Technology use	Yes, regularly	9	60.0%
	Yes, occasionally	4	26.7%
	No, but interested	2	13.3%
Confidence (1–5)	Mean = 4.00, SD = 1.00, Mdn = 4.0	—	—

2.3.3 Survey Instrument

The online survey consisted of fourteen items across five sections. Section 1 (Background) captured participants' professional role, years of experience, and frequency of technology use. Section 2 (Smart Technologies) included a confidence rating scale, a technology familiarity checklist, and two open-ended questions on perceived effectiveness and the benefits of real-time sensor data. Section 3 (Biohumus and Sustainability) addressed familiarity with biohumus as a chemistry topic, its perceived suitability for teaching, and student engagement with locally relevant content. Section 4 (Barriers and Support) explored structural obstacles to technology adoption and support needs. Section 5 (Reflection) invited practical advice and any additional observations. The survey was administered in English via Google Forms and remained open for one week; no personally identifiable information was collected.

2.3.4 Data Analysis and Survey Instrument Validity

Responses to closed items were summarised using descriptive frequency counts to describe the sample and identify patterns in technology use, barriers, and perceived student engagement. Open-ended responses were analysed using inductive thematic analysis (Braun & Clarke, 2006), through iterative reading, initial coding, and consolidation of codes into candidate themes. Four overarching themes were identified and confirmed as stable. Participant quotations were selected to illustrate each theme; minor grammatical corrections were made where necessary without altering meaning.

2.3.5. Content Validity of the Survey Instrument

Prior to distribution, all fifteen survey items were reviewed by a panel of five anonymous chemistry educators to validate the instrument. Each expert independently rated items on a five-point scale (1 = not relevant; 5 = highly relevant) for relevance, clarity, and appropriateness for the target population of chemistry teachers and university lecturers.

The overall expert rating was 3.84 out of 5.0, indicating acceptable content validity. Thirteen of the fifteen items received mean ratings of 3.50 or above. Two items received slightly lower ratings: Q14 (M = 2.20) may benefit from more refined response options in future iterations; Q2 (M = 2.20) received the lowest rating, which accounts for its lower rank in the statistical analysis. Both items were retained as essential to the research objectives; their ratings are noted as instrument limitations.

Inter-rater agreement was formally assessed using Kendall's Coefficient of Concordance ($W = 0.836$; $\chi^2 = 58.490$; $df = 14$; $p < .001$). The high W value reflects strong agreement and consistent positive endorsement across all five experts, confirming the survey's acceptable content validity prior to administration.

2.4 Ethical Considerations

Both phases of the study were designed and conducted according to ethical guidelines for educational research. In the quantitative phase, the student participants were informed about the study and that they could withdraw from the study whenever they wished, and that this would not affect their studies in any way; informed consent was obtained prior to the first session of the study, and the data were anonymised through numerical codes.

RESULTS

This chapter presents findings from both phases of the study. Section 3.1 reports quantitative results from the quasi-experimental pre-test/post-test design (Phase 1), addressing Research Questions 1 and 2. Section 3.2 presents qualitative findings from the teacher survey (Phase 2), addressing Research Question 3. Expert content validity data for both instruments are reported in the Methodology chapter (Sections 2.2.5 and 2.3.4).

3.1 Quantitative Findings (Phase 1: RQ1 and RQ2)

The quantitative phase examined whether IoT sensor technology produced significantly greater learning gains than conventional instruction in a biohumus-focused chemistry unit. Seventy-two third-year undergraduate chemistry students at SDU University participated (n = 36 experimental; n = 36 control). Data were collected via a 10-item multiple-choice test administered before and after the intervention. All analyses were performed in Jamovi (version 2.3) using non-parametric tests, as described in Section 2.2.5.

3.1.1 Descriptive Statistics

Table 3.1 presents the descriptive statistics for pre-test and post-test scores for both groups.

Table 3.1. Descriptive Statistics for Pre-Test and Post-Test Scores

	Experimental Group (n = 36)		**Control Group (n = 36)**	-
	Pre-Test	**Post-Test**	**Pre-Test**	**Post-Test**
Mean	2.75	8.19	2.31	6.08
SD	1.11	1.24	0.98	1.02
Median	3.00	8.00	2.00	6.00
Min	1	5	1	4
Max	5	10	4	8
Mean Gain	+5.44		+3.78	

Both groups began with low pre-test scores, confirming limited prior knowledge of biohumus chemistry and IoT monitoring. Following instruction, the experimental group achieved a mean post-test score of 8.19 out of 10 (81.9% accuracy), compared to 6.08 (60.8% accuracy) in the control group. The absolute mean gain of the experimental group (5.44 points) substantially exceeded that of the control group (3.78 points), providing an initial indication that IoT-integrated instruction produced stronger learning gains.

3.1.2 Baseline Equivalence

Before analysing intervention effects, a Mann-Whitney U test confirmed that the two groups did not differ significantly on pre-test scores ($U = 497$, $p = .077$). The groups were therefore comparable at the outset. To control for any residual pre-existing differences in subsequent analyses, gain scores (post-test minus pre-test) were used as the primary outcome measure rather than post-test scores alone, a well-established procedure in quasi-experimental research (Field, 2018).

3.1.3 RQ1: Effect of Smart Technology Integration on Learning Effectiveness

Research Question 1 asked: How does the integration of smart technologies enhance the effectiveness of teaching sustainable chemistry? This question was addressed through a between-group comparison of gain scores and post-test scores.

A Mann-Whitney U test on gain scores showed that the experimental group gained significantly more than the control group ($U = 306$, $p < .001$, $r = .529$). The effect size of $r = .529$ is classified as large (Field, 2018), indicating that the difference is not only statistically significant but also practically meaningful. On the post-test, the experimental group scored an average of 8.19 (81.9%) compared to 6.08 (60.8%) for the control group - a difference of approximately 2.1 correct answers out of 10, or 21.1 percentage points. A Mann-Whitney U test on post-test scores confirmed this between-group difference ($U = 138$, $p < .001$).

These findings provide a clear and robust answer to RQ1: the integration of smart IoT sensor technology produced significantly greater learning gains than conventional instruction, with a large effect size, across all applied statistical tests.

3.1.4 RQ2: Digital Tools and Student Comprehension of Biohumus Production

Research Question 2 asked: To what extent do digital tools and interactive learning methods improve students' comprehension of the biohumus production process? This question was addressed through within-group analysis of the experimental group.

A Wilcoxon Signed-Rank Test confirmed that the experimental group improved significantly from pre-test (Mdn = 3.00) to post-test (Mdn = 8.00), $W = 666$, $p < .001$. Every student in the experimental group showed improvement; no zero-gain or negative-gain cases were observed. The mean score increased from 2.75 to 8.19, a gain of 5.44 points, confirming that IoT-integrated instruction produced consistent and meaningful improvements in student comprehension of biohumus production.

Notably, the control group also improved significantly between pre-test and post-test (mean gain = 3.78), demonstrating that the biohumus content itself, delivered through structured conventional instruction, was pedagogically effective. However, the between-group analysis (Section 3.1.3) confirms that the gain achieved through IoT-integrated instruction was significantly larger ($U = 306$, $p < .001$, $r = .529$). The answer to RQ2 is therefore that digital IoT tools produced a significant and consistent improvement in comprehension - and that this improvement substantially exceeded what was achieved through conventional means.

Table 3.2. Summary of Statistical Tests

Comparison	Test	Statistic	p-value	Effect Size (r)
Experimental pre vs. post	Wilcoxon	W = 666	< .001	—
Baseline (pre-test) between groups	Mann-Whitney U	U = 497	.077	—
Gain scores (Exp > Control)	Mann-Whitney U	U = 306	< .001	r = .529
Post-test between groups	Mann-Whitney U	U = 138	< .001	—

3.2 Qualitative Results: Teacher Survey Findings

3.2.1 Overview

The qualitative phase addressed Research Question 3: Which smart technologies are most effective in fostering sustainable knowledge and skills in the field of green chemistry? An online survey was conducted with 15 practising chemistry teachers and university lecturers. Descriptive statistics were used to summarise closed items; inductive thematic analysis (Braun & Clarke, 2006) was applied to open-ended responses. Four main themes emerged. A full profile of survey participants is provided in Table 2.1 (Section 2.3.2).

Two-thirds of participants had less than three years of teaching experience, potentially limiting the qualitative findings. (66.7 %). Early career teachers have a greater willingness to use new technologies, and they also have a higher comfort level with various digital tools. This is because they completed their education during a time of rapid technological advancement (Wohlfart et al., 2023). This skew suggest that the attitudes and confidence level that were reported in this survey including an average score of 4.00 out of 5.00 is more likely to be more positive towards smart technologies than a more experience-diverse sample. Teachers with longer careers may face other obstacles, have established teaching habits, or require more professional learning before adopting IoT-based tools.

The inclusion of open-ended questions encouraged respondents to share detailed opinions based on their professional practice. These responses provided contextual information that could not be captured through numerical measures alone and helped identify recurring patterns across participants' experiences. Through thematic analysis, common viewpoints were grouped into broader categories, allowing key themes related to technology effectiveness, accessibility, and educational value to emerge from the data.

Subsequent studies should recruit a more balanced sample across experience levels to triangulate and obtain a fuller picture of the practitioner perspectives regarding the integration of smart technologies in chemistry education.

This approach allowed for a broader understanding of how technology can contribute to sustainable knowledge development in the context of green chemistry education.

3.2.2 Technology Familiarity

The technologies most commonly identified by participants as familiar or used were virtual laboratories and simulations (13 of 15), followed by AI-based learning platforms (10), digital data visualisation tools (10), and smartboards (8). Six respondents reported familiarity with IoT sensors - the technology central to the present study - making it the fourth most widely used tool in the sample.

When asked to nominate the single most effective technology for supporting chemistry understanding, five participants selected virtual laboratories and simulations, four chose VR/AR tools, three chose AI-based platforms, and two nominated IoT sensors. This pattern suggests that while IoT sensors are considered useful, practitioners currently regard virtual simulations as the most practically available technology for conducting chemistry experiments. The thematic analysis below, however, reveals a more nuanced picture when participants were asked specifically about real-time sensor data.

3.2.3 Biohumus as a Teaching Topic

Participant familiarity with biohumus production varied considerably: eight participants (53.3%) described themselves as "somewhat familiar," three (20.0%) as "very familiar - I have taught it," and four (26.7%) as "not familiar at all." Despite this uneven familiarity, endorsement of biohumus as a suitable teaching context was strong and unanimous in direction. No participant responded "no." In total, 86.6% of respondents - including those with no prior knowledge of the topic - considered it at least potentially suitable for teaching green chemistry at university level.

This widespread approval highlights a shared recognition among educators of the practical value that sustainable agricultural concepts bring to the chemistry curriculum. Consequently, integrating biohumus production could serve as an effective, real-world framework to bridge theoretical green chemistry principles with

tangible ecological practices.

Table 3.3. Perceived Suitability of Biohumus as a Green Chemistry Teaching Topic (n = 15)

Response	n	%
Yes, definitely	8	53.3%
Yes, with some modifications	5	33.3%
Not sure	2	13.3%
No	0	0.0%

3.2.4 Student Engagement with Real-World Topics

Participants were asked how students respond to current, locally relevant topics in chemistry classes. The results were very favourable: eight participants (53.3%) said students were “much more engaged than with traditional topics”, five (33.3%) reported they were “slightly more engaged”, and two (13.3%) said there was “no difference”. No participants said that real-world content made students less engaged.

Table 3.4. Perceived Student Engagement with Real-World Chemistry Topics (n = 15)

Response	n	%
Much more engaged	8	53.3%
Slightly more engaged	5	33.3%
No difference	2	13.3%
Less engaged	0	0.0%

All in all, 86.6% of respondents reported that when chemistry was associated with real-world, locally relevant contexts, student engagement increased. The finding provides practitioner-level validation for one of the key pedagogical assumptions of the present study, namely that biohumus production is a locally visible and practically meaningful topic which would motivate students more than material from a textbook. This suggests that shifting from traditional, abstract exercises to contextualized learning experiences is essential for fostering sustained academic interest and deeper conceptual comprehension among learners.

3.2.5 Main Barriers to Technology Adoption

Table 3.5. Main Barriers to Smart Technology Use in Chemistry Teaching (n = 15)

Barrier	n	%
Time constraints (curriculum pressure)	5	33.3%
Lack of equipment / devices	4	26.7%
Lack of training / professional development	3	20.0%
Technical difficulties / unreliable internet	1	6.7%
Lack of student interest	1	6.7%
No barriers	1	6.7%

The most common barrier was time limitation due to syllabus pressure (33.3%) followed by lack of equipment (26.7%) and lack of training (20.0%). A university lecturer with over 20 years of experience reported no barriers at all, according to just one participant. Such findings indicate that the barrier preventing the integration of smart technologies is structural rather than motivational: the majority of teachers involved are indeed willing and interested, but they work within structures that do not yet allow for the time and other resources needed.

3.2.6 Thematic Analysis of Open-Ended Responses

Theme 1: Real-Time Data Visualisation as the Core Pedagogical Advantage of IoT

Analysis of responses to questions about the benefits of IoT devices revealed that the most consistently identified advantage was the capacity for continuous, real-time visualisation of chemical and biological processes. This theme appeared in 11 of 15 responses, making it the most prominent finding across the open-ended data.

Participants described this advantage in strikingly similar terms, using phrases such as "hidden transitions," "live graphs," "dynamic visualisation," and seeing "the entire process" to distinguish sensor data from the static snapshots provided by pH strips or thermometers. One participant observed: "The biggest advantage of using real-time IoT sensors over traditional tools is the ability to see the hidden transitions." Another described the shift more precisely: "Real-time dynamics: instead of just before

and after, students see a live, continuous graph. This reveals the exact moment a reaction peaks or changes."

A related sub-theme concerned cognitive load reduction. One participant noted that automating data collection removes the manual stress of recording measurements, allowing students to focus on why a reaction is happening rather than simply that it is happening. This observation aligns with the quantitative findings in Section 3.1: if real-time visualisation redirects student attention from data collection to data interpretation, it would be expected to produce the kind of conceptual gains - rather than mere procedural gains - reflected in the experimental group's significantly higher post-test scores.

Theme 2: Smart Technology and Sustainable Chemistry Are Seen as Naturally Complementary

Across many responses, participants did not treat smart monitoring technologies and sustainability-oriented chemistry as separate or incidentally connected topics; instead, they described them as naturally and structurally aligned. One participant stated: "Smart technologies and sustainability should not be treated as separate topics but as naturally connected." Another was more explicit: "One crucial point is that smart technologies and sustainability - green chemistry - are perfectly matched."

A particularly significant observation came from one respondent who connected the means and the ends of the pedagogical approach: "With sensors, we can do micro-scale chemistry. This means that we can measure in a manner that is already consistent with green chemistry - aimed at reducing waste and consumption of resources." This comment suggests that IoT sensors do not merely serve as tools for teaching green chemistry; they can themselves embody its principles (minimal intervention, process control, waste reduction), offering a pedagogical coherence unavailable through simulation-based technologies.

Theme 3: Structural Barriers Outweigh Motivational Ones

Open-ended responses about barriers and support needs consistently revealed that obstacles to technology integration are structural — primarily time, equipment,

and training - rather than motivational. All participants indicated receptiveness to smart technologies in principle; those who had not yet used such tools described themselves as interested rather than opposed.

The structural nature of barriers was most clearly reflected in the kinds of support participants requested. Rather than persuasion or inspiration, they asked for concrete, ready-to-use resources: curriculum-aligned lesson plans that show exactly how to incorporate IoT or AR into a standard chemistry unit; a reliable hardware kit; pre-built and editable digital lab templates aligned to specific curricula; and dedicated technical support. As one participant summarised: "Teachers need curriculum-aligned lesson plans. They show exactly how to use tools like IoT or AR in a standard chemistry unit. In addition, they will also need a reliable hardware kit." The policy implication is direct: if chemistry educators broadly support technology integration but are prevented from implementing it by resource constraints, the solution is resourcing - not advocacy.

Theme 4: Start Small - A Universal Practitioner Recommendation

Regardless of background or experience level, participants converged on a common piece of first-time advice: begin with a single, visually engaging, conceptually clear experiment before attempting broader integration. This recommendation appeared, in various formulations, in 10 of 15 responses.

Representative statements included: "Start simple and focus on pedagogy, not technology"; "Initiate with one sensor - whether pH or temperature - to create a wow effect"; "Start small. Don't try to digitise every experiment at once"; and "First demonstrate, then give students an opportunity to try with clear guidelines and instructions." The most experienced participant - a university lecturer with over twenty years of practice - elaborated: "Using a small experiment setup is a great start. It is not necessary to replace existing equipment. Pick one simple process, like an acid-base titration, and use sensors alongside traditional methods first, so students can compare the differences themselves."

The uniformity of this recommendation across a heterogeneous sample suggests it reflects genuine practitioner wisdom rather than a context-specific observation. The

main risk of technology integration, according to participants, is not technical failure but pedagogical overreach: attempting too much before either teacher or students have the fluency to make the technology serve learning rather than distract from it.

3.2.7 Summary

The survey findings were consistent across participants and mutually reinforcing. Descriptive analysis revealed a sample with high technology confidence, strong endorsement of biohumus as a green chemistry teaching context, and near-universal agreement that locally relevant content increases student engagement. The primary barrier to adoption was found to be structural - principally time pressure - rather than attitudinal.

Thematic analysis produced four salient findings: real-time visualisation as the core mechanism through which IoT sensors create educational value; the natural alignment between smart monitoring technologies and sustainable chemistry pedagogy; structural rather than motivational barriers to adoption; and the universal practitioner wisdom of beginning small and keeping pedagogical purpose at the centre of design.

Taken together, the qualitative findings extend and enrich the quantitative results reported in Section 3.1. While the pre-test/post-test analysis demonstrates that IoT-integrated instruction produces significantly greater learning gains ($U = 306$, $p < .001$, $r = .529$), the teacher survey begins to explain why - through the eyes of practitioners who have observed students engaging with digital tools across a range of classroom settings.

DISCUSSION

4.1 Overview

This chapter explains the results from Chapter 4 in relation to the three research questions and the theory from the literature review. The discussion uses the numerical pre-test/post-test evidence along with the teacher survey evidence, looking at how these two pieces of evidence support, add to, and in some cases challenge each other. As relevant, the findings are linked to wider international research regarding the use of smart technologies in chemistry teaching and on sustainable chemistry education.

4.2 The Impact of Smart Technology Integration on the Effectiveness of Sustainable Chemistry Teaching

Response to RQ1 is provided through quantitative evidence and qualitative evidence. The experimental group gained significantly more learning than the control group on a quantitative measure ($U = 306$, $p < .001$, $r = .529$, large effect). Out of the fifteen teachers surveyed, eleven independently identified real-time data visualization as the primary way in which IoT is enhancing the teaching of chemistry. This provides a practitioner-level explanation of the observed quantitative advantage.

The quantitative analysis yields a clear and statistically robust answer to this question. The experimental group's students, who employed an intelligent soil detector (IoT sensor) in their laboratory sessions, showed a greater learning gain compared to the control group’s students, who employed conventional measuring instruments. The between-group difference in gain scores was statistically significant ($U = 306$, $p < .001$) with a large effect size ($r = .529$), and the post-test scores of the experimental group were significantly higher than those of the control group ($U = 138$, $p < .001$). The outcomes show that smart technology integration has not only novelty value but also brings about a statistically and practically significant enhancement in what students learn.

To better understand the importance of this finding in practical terms, it is worth looking at the numbers. The students in the experimental group answered an average of 8.19 out of the ten post-test questions correctly (81.9%) in comparison to 6.08

questions (60.8%) for the controls. Thus the difference of almost 2 questions out of 10 between the two groups is statistically strong and meaningful for learning. A student who answers 8 out of 10 questions correctly shows sound conceptual understanding; a student who answers 6 out of 10 can be said to have partially but incompletely acquired the knowledge. The IoT-integrated instruction caused students, on average, to progress from partial to solid understanding which conventional instruction was effective but not consistent.

Nevertheless, did the technology actually help, and if so, then *in what way*? The teacher survey's qualitative data provides an explanation at the practitioner level. Out of the fifteen respondents, eleven mentioned that real-time data visualization is the key mechanism through which IoT sensors support chemistry learning. This refers to the ability to continuously illustrate a chemical or biological process, rather than just the measurements taken at the specified time, as expressed by one veteran university instructor with more than twenty years of practice.

This explanation aligns with the research on mental effort discussed in Chapter 2. Specifically, when students use thermometers or pH strips as instruments, measuring involves relatively more mental effort than when reading physical scales, matching colors, and recording data by hand. The incorporation of Internet of Things (IoT) sensors allows automation of the various steps in a scientific experiment so that students can concentrate more on the understanding of concepts and thinking about the results. Survey data highlights this benefit, with one teacher observing that students can investigate reaction causes instead of managing the "manual stress of recording measurements." Moving away from mere data collection encourages analytical processing, which drives meaningful cognitive development rather than surface-level lab habits.

According to Abichandani et al. (2022) and Ghashim and Arshad (2023), IoT-enabled learning environments support more profound engagement with data interpretation and offer more sustained inquiry behaviours than conventional instruction. The data from SDU University's Abilbek et al. (2025) thirty-day IoT

watching of biohumus shows that continuous sensor data reveals the complexity of the system, such as nonlinear interactions between change of temperature, moisture, pH, and fertility of the soil, which cannot be traced by discrete manual measuring. When students experience this complexity through their own sensor readings, they are confronted with real science that requires reasoning rather than recall.

The present study can therefore not completely disentangle the effect of the technology from other aspects of the experimental condition. The experimental group underwent the same lecture content and video demonstration as the control group. However, the overall learning experience including the density of feedback, immediacy of data, and nature of analytical task was qualitatively different. Subsequent investigations utilizing more stringent control conditions or integrating measures that capture student reasoning throughout the lab session would serve to elucidate the precise contribution of the IoT sensor to the heightened gains observed.

With respect to instrument validity, the content validity of the pre-test and post-test was confirmed valid by the expert panel (overall mean rating = 4.44 of 5.0). The high agreement of the five experts (Kendall's W = 0.900 for pre-test; W = 0.873 for post-test; W = 0.855 for survey) indicates that the experts gave the items in a similar, positive way. Item Q7, which addressed the technical dissimilarities among sensor types, received a lower mark (M=3.40). The design of the instrument probably has a shortcoming. Future research could substitute technical queries with questions that assess students' understanding of chemistry concepts better. The finding is supported by expert validation that the learning gains are real and imply improved knowledge of chemistry and not a result of a poorly designed test. Consequently, this rigorous verification process confirms that the evaluation tools are highly suitable for measuring academic performance while simultaneously minimizing potential biases and reinforcing the overall trustworthiness of the empirical findings.

4.3 The Role of Digital Tools and Interactive Learning Methods in Improving Students' Comprehension of Biohumus Production

The Wilcoxon signed-rank test confirmed that the experimental group improved significantly from pre-test to post-test ($W = 666$, $p < .001$), with all students showing improvement and no negative gains recorded. This finding directly answers RQ2 - IoT-integrated instruction produced a consistent and meaningful improvement in students' comprehension of biohumus production. The study revealed that even students with access to conventional tools experienced significant gains. This finding has implications beyond the question of technology and is worth reflecting on.

At the start of the study, the experimental group had a low baseline score ($M = 2.75$ out of 10), showing limited prior familiarity with biohumus chemistry and IoT monitoring. Following four sessions of IoT-integrated instruction, the experimental group achieved a mean post-test score of 8.19 — a gain of 5.44 points. The between-group comparison further confirmed that this improvement was significantly greater than that of the control group ($U = 306$, $p < .001$, $r = .529$), providing clear evidence that digital tools enhanced student comprehension of biohumus production. It is a highly important finding in the area of green chemistry education. The fact that the topic of biohumus production is not merely a comfortable example for specialists in chemistry but a pedagogically significant example makes this clear. The qualitative data strongly supports this conclusion. A recent survey presented educators with the question, "Do you consider biohumus production suitable for imparting green chemistry principles?", to which 86.7% responded affirmatively. Furthermore, 86.7% reported that students engage better with local materials and issues than traditional textbook topics. One respondent stated in a nutshell:

A teacher feels it's vital to show students that chemistry is not only found in a textbook.

This evidence coincides with findings in hands-on learning research as noted in Chapter 2. Karpudewan & Ahmad (2026) highlight that local relevance is a prime factor motivating students in green chemistry education. Students who connect the chemistry they study in class to an explicit and unsolved problem their community is

facing are much more likely to engage deeply with the subject. The local context in Kaskelen, which faces an urgent and obvious problem in organic waste management, is not fictitious, but real. This is seen in the work of Abilbek et al. (2025) that proves how serious the problem is and how biohumus can help.

The biochemical richness of the topic also contributes to its didactic efficiency. As outlined in Chapter 2, when biohumus is produced, nitrogen mineralization occurs and pH regulation is achieved. Furthermore, humification chemistry is involved. Also, enzymatic activity plays a role in the breakdown of organic matter. Using a structured laboratory worksheet, the study required students to think across all these fronts at once by determining which of the soil containers was optimal, diagnosing what was exceptionally wrong with the others, and suggesting evidence-based remedies. Green chemistry education aims to create precisely the type of integrative analytical task just undertaken. The statistically significant pre-to-post gains in the two groups suggest that meaningful comprehension gains can occur through relatively brief, structured exposure to the topic.

The between-groups analysis supports this finding; the experimental groups improved internally and gained significantly more than the control group ($U = 306$, $p < .001$, $r = .529$). The biohumus content is the topic of both attention groups, but the results of comprehension are better with IoT technology.

4.4 The Effectiveness of Smart Technologies in Fostering Sustainable Knowledge and Skills in Green Chemistry

Evidence for this question mainly comes from teacher survey data, while some evidence could come from experimental results. An extensive review of the literature also provides some supportive evidence. Participants of the survey most frequently identified virtual laboratories and simulations as effective educational technologies in chemistry (five participants), followed by VR/AR tools (four participants), AI-based platforms (three participants), and IoT sensors (two participants). Findings show that, compared to other technologies, IoT sensors are less effective. A careful reading of the qualitative responses reveals an important caveat. When participants were asked

specifically about the benefits of gaining insight into *real-time sensor data* and not technology in general, the responses were much more unequivocally positive and specific about IoT as a technology, as compared to the responses about VR and simulation.

The participants distinguished between technology that *simulates* chemistry and that which *monitors* real chemistry. Simulations and virtual laboratories generate real-life representations of chemical processes, although they are artificial. These real-time IoT sensors pick up data from real processes, hence real soil, real earthworms, and real biochemical transformations. Several subjects noted this difference explicitly.

> The ability of smart technologies to harness and measure micro-scale chemistry is reinforcing the links between sustainability and chemistry. By enabling IoT sensors to operate at the micro level, we are able to reduce waste and resource consumption in their design – a principle enshrined in green chemistry whose measures mitigate harm at the very level of measuring.
>
> *"Smart technologies and sustainability (Green Chemistry) are perfectly matched."*

The fact that the means used, namely the technology itself, also acts as an end (the technology is designed and used according to the principles of green chemistry) offers a unique advantage of IoT sensors over virtual ones in sustainability education. A student who observes a real biohumus system with a real sensor is not only learning green chemistry, but implementing it.

The qualitative data further divulged a hierarchy of conditions under which the IoT sensors perform effectively. Participants steadily propose to start with a single experiment that is massively visual and one that provides an immediate and intelligible connection between the response of the sensor and chemical reality; for instance, a pH sensor being used in an acid-base titration, a temperature probe in a reaction calorimetry experiment, or a soil moisture detector being used in a composting system. Ten of fifteen respondents made the 'start small' suggestion. This indicates that not the IoT technology itself, but rather the right pedagogical design makes use of IoT educationally effective. In this sense, the educational effectiveness is dependent on the

teacher's ability to frame the sensor data as a window into chemical processes rather than as an end in itself.

This result has a direct link to the establishment in Chapter 3 of the literature review that teacher readiness-pedagogical content knowledge for green chemistry-is the most important determinant of whether any given technology produces learning. According to Wohlfart et al. (2023), the use of ICT tools in chemistry learning improves the learning outcomes only when it is embedded within a structured pedagogical framework. However, if ICT is simply added to what has been already done, the learning outcome is not effective; thus, a pedagogy based on an ICT-preferring tool is a must. The outcome of the present study corroborates this: it was not simply the measuring device that caused the experimental group to have an advantage over the control, but this measuring device combined with an appropriate pedagogy. The worksheet and quick reference guide refocused student attention on chemical reasoning at a moment when that reasoning was at its most productive possible, by virtue of having a device within the structured context of the laboratory.

4.5 Barriers, Implications, and the Road Forward

According to the teacher survey, the most cited barrier relating to smart technology was a lack of time (33.3%), followed by a lack of equipment (26.7%) and a lack of training (20.0%). The incorporation of smart technologies into sustainable chemistry education does not fall under the umbrella of teacher attitude as a challenge, nor student motivation. The groups in the current study exhibited significant learning gains; those who were surveyed came across as almost universally positive regarding the educational power of the IoT and related tools. The barriers are the structure of overloaded curricula, insufficient equipment budgets, and teacher preparation systems that have not yet adapted to the pedagogical demands of technology-enhanced sustainability education.

Structural solutions are indicated by this diagnosis. Throughout the surveys, the option that came out most consistently as a 'must-have' was curriculum-aligned resources-basically pre-built lesson plans and lab templates that show teachers how to

incorporate smart tools into existing courses and lesson plans without making them redesign everything from scratch. It would be very effective and easy to adopt institutional support that will significantly lower the barrier to adoption.

The current study's findings add to the resource base. The four-session intervention design, which incorporates lecture, video demonstration, and an IoT-supported laboratory structured worksheet, may be an adaptable pedagogical framework for chemistry teachers working with biohumus or similar sustainability issues. Ultimately, this flexible model can create significant educational value under various technological conditions.

CONCLUSION

Overview

This chapter summarizes the findings of the research study and discusses its implications for chemistry education, sustainable pedagogy, and smart technology integration in university teaching. In this section, the core research questions are revisited, the important conclusions of this study are summarised, the contribution of this study to theory and practice is listed, recommendations are made to teachers and institutions, and future research directions are suggested.

Summary of Key Findings

The present study investigated the effect of smart Internet of Things (IoT) sensor technology on promoting sustainable chemistry instruction as applied in the context of biohumus production. This study was conducted in Kaskelen, Kazakhstan's SDU University. For this, a mixed-method design was used. This included a 72 third-year undergraduate chemistry student's quasi-experimental pre-test/post-test study. Furthermore, there was a 15 expert online survey involving chemistry teacher's and university lecturer's involvement.

The results from both phases of the study were consistent and supported each other.

In answer to RQ1, which seeks to show how *integration with smart technologies improves the effective teaching of sustainable chemistry,* a quantitative analysis has shown that students who use IoT sensors for laboratory instruction have significantly higher learning gains than those who use conventional measuring tools ($U = 306$, $p < .001$, $r = .529$). Such a large effect size indicates that the result is both statistically significant and meaningful. The qualitative data explored this finding more deeply. Educators identified real-time visibilization of data as the number one way in which IoT sensors enhance learning. Utilizing this method, learners can view chemical phenomena in action throughout an experiment rather than at points of measurement. Data collection is less of a focus for students, allowing them to center on interpretation and reasoning instead.

In answer to RQ2 regarding the extent to which *learning digital tools and interactive learning improved students' understanding of the process of managing the production of biohumus*, it was found that the pre-test and post-test of both experimental and control groups improved significantly ($p < .001$ for both). The mean score of the experimental group increased from 2.75 to 8.19 - a gain of 5.44 points - confirming that IoT-integrated instruction produced significant and meaningful improvement in student comprehension. The between-group analysis ($U = 306$, $p < .001$, $r = .529$) confirmed that this gain was significantly greater than that of the control group, directly answering RQ2. The teacher survey provided support for this conclusion, with 86.7% of respondents agreeing that biohumus was an appropriate context for green chemistry teaching, and the same share finding more student interest in what chemists do and the local relevance of chemistry.

In response to RQ3-*what types of smart technologies are most effective in developing sustainability knowledge and skills in green chemistry?*-the qualitative evidence indicated that IoT sensors are particularly well-suited to sustainability-focused chemistry education. That is not only because they generate accurate and real-time data but because they generate real data from real processes. IoT sensors can monitor chemistry as opposed to simulating it virtually. The difference matters for green chemistry education especially because when students use sensors to see the moisture, pH, and temperature of a living vermicomposting system, the very act of using the technology is in itself an expression of green chemistry principles: minimal intervention, real-time process control, and waste valorisation. There was a strong recommendation from practitioners to start integration through one visually interesting experiment and keep pedagogical purpose (not technology novelty) at the core of design.

Theoretical Contributions

The findings of this study produce important contributions to the literature on smart technologies in chemistry education as well as sustainable chemistry.

To begin with, it supplies empirical evidence of a Central Asian educational setting which is exceedingly underrepresented in the international literature of the efficacy of IoT-integrated instruction in green chemistry. Existing studies on smart technologies in chemistry education are almost exclusively from Western Europe, East Asia, or North America. The current results show that the instructional benefits of IoT sensor technology are not context-specific: they are visible at a Kazakhstani university, with students from a secondary education system, that traditionally emphasizes theoretical over inquiry-focused learning.

Furthermore, the paper adds to a nascent body of literature on the use of biohumus production as a pedagogical object in green chemistry education. Although biohumus has been thoroughly researched as a practice for agriculture and waste management, very few studies have systematically investigated its teaching potential as a context for sustainable chemistry.

The evidence presented in this study, whereby significant comprehension gains have been obtained in both technologically enhanced and traditional scenarios through biohumus-focused instruction, suggests that this topic is worthy of a greater place in green chemistry curricula.

Third, the study's mixed-methods design shows how quantitative outcome evidence and qualitative practitioner knowledge can be productively integrated in educational research. The data from the pre-test/post-test determined that the incorporation of IoT is effective, and the teacher survey initiated the process of explaining why and under what conditions. Neither form of evidence would have given the whole story alone.

Practical Recommendations

Based on the results of the study, the following recommendations are provided to the chemistry teachers, curriculum developers, and school leaders.

Initial IoT integration should target specific laboratory tasks where real-time sensor metrics yield straightforward, conceptually significant outcomes. Suitable benchmarks include tracking pH fluctuations during neutralization, mapping

temperature profiles in decomposition reactions, or monitoring moisture dynamics throughout biohumus production. Educators must explicitly connect these digital readouts to underlying chemical principles, transitioning from passive content delivery toward structured, analytical classroom discussions.

For curriculum designers: Biohumus production should be considered for inclusion in sustainable chemistry curricula, not as an isolated practical exercise but as a sustained, multi-session project that allows students to observe chemical processes over time. According to this study, a four-session model is sufficient to produce significant gains in comprehension. On the other hand, a semester-long project would most probably foster deeper systems thinking and more durable knowledge. The IoT sensor monitoring should be a built-in aspect of such a project and not a technological add-on.

Smart technology is less likely to be adopted by survey respondents because of structural issues like time, equipment and training as opposed to attitudinal issues, institutional leaders suggest.

Directions for Future Research

This study raises several questions that future research should address.

The present study measured knowledge immediately before and after a four-session intervention. It is not known whether the gains in both groups are maintained over the longer term-a semester, a year. A post-test conducted after a few months of intervention would be proof of sustained learning with IoT.

The generalisability of the results in the quasi-experimental design experiment is limited despite the results being reliable. This is because of the smaller sample with 36 students per group. Therefore, the first factor to develop is **more extensive and diverse samples**. The external validity of conclusions can be substantially strengthened through a larger multi-site study at several universities or schools throughout Kazakhstan or across countries.

Qualitative results point towards teacher readiness being at least as important as technology in impacting learning outcomes. Research that specifically monitors

changes in teacher pedagogical content knowledge before and after professional development that focuses on training teachers in Internet of Things (IoT), and the subsequent effects of that professional development on student outcomes, would fill a gap in the literature.

A qualitative inquiry into student reasoning: The current study assessed what students were able to learn through a multiple-choice assessment. It did not record how they made sense of the data, what questions they asked when looking at sensor data, how they changed their understanding when data were inconsistent with their expectations, and what connections they made to relevant chemical parameters and the living system they studied. Using think-aloud protocols, observing laboratory sessions, or analyzing worksheet responses would yield far richer evidence about the cognitive processes through which IoT-enhanced learning occurs.

The opportunity to present my work at ICEDU 2026 in Bali gave rise to the expansion of the study. Dr. Wiets Botes from Sol Plaatje University (South Africa) was of the view that it would be worthwhile to conduct a cross-national project to understand the use of smart technology in sustainable chemistry education globally. The countries are endowed with unique infrastructures, cultures, policies, and institutional strengths. This collaboration would enable the Kazakhstani outcomes to be put into a more global setting and mitigate the geographic limitations of the study. I intend to further develop these ideas in my doctoral thesis and build on the theories and methodologies set out in this dissertation through an ongoing programme about smart technology and sustainability education in Central Asia and beyond. My doctoral research agenda will benefit directly from feedback from the ICEDU 2026 evaluation panel, including a wider group of participants, long-term research designs, and institutional policies.

Expert interview evidence: Dr. Wiets Botes, of Sol Plaatje University, South Africa was identified (through participation at ICEDU 2026 in Bali, seeing that he proposed a research collaboration) and contacted for an expert interview as part of the qualitative data collection. No written response was received in time for the present

study. The potential collaboration provides a valuable opportunity for cross-national research in the future. The doctoral research program mentioned above will try to include his expert view through a formal interview.

Concluding Reflections

A straightforward question was posed at the start of the present study: Does the connection of a chemistry classroom to a sensor network change what students learn? Yes, the evidence suggests, significantly and measurably, and in a way that can be explained by the mechanisms that the literature would predict. Even the students working with no sensors, but merely a thermometer and pH strips in front of the three containers of soil and biohumus, educated themselves very deeply on the sustainable chemistry front over the course of four fifty-minute sessions.

This implies that technology does matter, but so do the specifics of the content; the structure of the task; and the local context that makes the topic appear relevant and not abstract. The example of biohumus production in Kaskelen is not a made up one used for teaching purposes. This is a real process addressing a real challenge for a community that never managed its organic waste and whose soil of the nearby agricultural fields can benefit from whatever students learn to produce. Chemistry classes which take this seriously – that think of the local environment as a laboratory and local problems as research subjects – will not need to manufacture student engagement. It finds it already available.

Smart technology makes the invisible visible at its best. The biochemistry of a composting system is rendered into data that students can gaze upon, question, and reason with. However, the real potential of this contribution is truly realized when the technology is used by a teacher who knows what questions to ask and a student who is given a rationale to be concerned about the answers.

LIMITATIONS

This study was conducted in a real university setting, not a controlled laboratory, and that distinction matters for how the findings should be read.

The most important constraint is the research design itself. Students were not randomly assigned to groups - they were already enrolled in their sections before the study began. Although the pre-test confirmed that both groups started at a similar level, it is impossible to completely rule out that some unobserved difference between them, whether in motivation, digital experience, or prior academic background, contributed to the results alongside the intervention itself.

The study was also conducted at a single institution with a relatively small sample: 36 students per group at SDU University in Kaskelen. The findings are internally consistent and statistically robust, but they represent one course, one city, and one educational context. Whether the same approach would produce similar results at a different university, or in a system with weaker digital infrastructure, is something this study cannot confirm.

The intervention lasted four sessions across one month. That was enough time to produce clear and measurable learning gains, but not enough to know whether students retained that knowledge weeks or months later.

The assessment format also has limits. Multiple-choice questions are consistent and easy to score, but they only show what students can recognise - not what they can reason through independently. As individual item responses were not recorded separately, Cronbach's alpha could not be calculated; this represents a minor limitation of the instrumentation.

On the qualitative side, the teacher survey was dominated by early-career educators - two thirds of participants had fewer than three years of experience. Their perspectives are valuable, but the views of more experienced teachers are underrepresented here.

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APPENDICES

Informed Consent Form ***Appendix 1***

Research Title: Impact of Smart Technologies on Teaching Sustainable Chemistry: A Focus on Biohumus Production

Researcher: Abdybekova Azhar (Master's Student, SDU University)

Supervisor: Zhangyl Abilbek

Purpose of the Study: You are invited to participate in a research study designed to evaluate the use of digital IoT sensors in learning chemical and biological parameters of biohumus.

Confidentiality & Anonymity: Your participation is strictly anonymous. Please do not write your real name on the tests; use your Student ID or a unique nickname. The data collected will be used solely for academic research and statistical analysis (SPSS).

Voluntary Participation: Your participation is entirely voluntary. You may refuse to participate or withdraw from the study at any time without any negative consequences to your grades or academic standing.

Consent: By signing below, I confirm that I have read and understood the information above, and I freely agree to participate in this study.

Participant's Signature: _____ **Date:** _____

(Please detach this page and return it to the researcher before the lesson begins).

Pre-Test Instrument ***Appendix 2***

Student ID or Nickname: _____ *(Please remember this for the Post-test)*

Group: [ ] Control [ ] Experimental

SECTION 1: Background Information *Please tick (✓) the appropriate box:*

1. Where did you spend most of your childhood?

[ ] Urban area (City / Town)

[ ] Rural area (Village)

2. Have you ever seen the practical process of making "biohumus" (vermicomposting)?

[ ] Yes, I know it well [ ] I have heard of it, but have no practical experience [ ] No, I have never heard of it

---

SECTION 2: Academic Knowledge

Instructions: Please circle or tick the correct answer.

1. What is the primary objective of "Waste Valorization" in modern green chemistry?

a) To burn organic waste for energy. b) To convert organic waste into high-value organic fertilizer (biohumus). c) To store waste in plastic containers.

2. What is the ideal Carbon-to-Nitrogen (C:N) ratio for efficient vermicomposting?

a) 5:1 b) 25:1 to 30:1 c) 100:1

3. Which chemical parameter is most critical to prevent "acidosis" in worms?

a) Stable pH levels (ideally 6.5–7.5). b) High light intensity. c) Low oxygen levels.

4. Why is maintaining 60-80% moisture essential for the biochemical transformation?

a) It prevents the plastic bin from melting. b) It facilitates the movement of nutrients and supports aerobic respiration. c) It cools down the environment.

5. What is the safe temperature upper limit for microbial and worm activity?

a) 15°C b) 35°C c) 65°C

6. In sustainable chemistry, what is the main advantage of using Smart IoT sensors (like an Intelligent Soil Detector)?

a) It looks more professional in a laboratory. b) It provides precise, real-time data to react to chemical fluctuations instantly. c) It eliminates the need to understand chemistry.

7. Why are "Capacitive" sensors preferred over "Resistive" ones in biohumus monitoring?

a) They do not corrode easily in wet, chemical environments. b) They are smaller and cheaper. c) They measure sunlight.

8. SCENARIO: If your digital detector shows a sudden drop in pH from 7.0 to 4.5, what chemical intervention is needed? a) Add more water. b) Add a neutralizing alkaline agent (like calcium carbonate/eggshells). c) Add more acidic food waste.

9. SCENARIO: A correlation between high temperature (>35°C) and extremely low moisture (<40%) typically results in:

a) Optimal, high-quality biohumus. b) High worm mortality and cessation of the decomposition process. c) Faster growth of plants.

10. How does the integration of AI and Smart Technologies benefit education in chemistry?

a) By completely replacing teachers with robots. b) By developing students' analytical and problem-solving skills through real-time data visualization. c) By making the final exam easier.

Post-Test Instrument ***Appendix 3***

Student ID or Nickname: _____ *(Must be the SAME as your Pre-test)*

Group: [ ] Control [ ] Experimental

SECTION 1: Academic Knowledge & Scenario Analysis

Instructions: Please circle or tick the correct answer. (Note: Questions have been randomized).

1. SCENARIO: If your digital detector shows a sudden drop in pH from 7.0 to 4.5, what chemical intervention is needed?

a) Add more acidic food waste. b) Add a neutralizing alkaline agent (like calcium carbonate/eggshells). c) Add more water.

2. What is the safe temperature upper limit for microbial and worm activity?

a) 35°C b) 15°C c) 65°C

3. Why is maintaining 60-80% moisture essential for the biochemical transformation?

a) It cools down the environment. b) It prevents the plastic bin from melting. c) It facilitates the movement of nutrients and supports aerobic respiration.

4. How does the integration of AI and Smart Technologies benefit education in chemistry?

a) By developing students' analytical and problem-solving skills through real-time data visualization. b) By making the final exam easier. c) By completely replacing teachers with robots.

5. What is the primary objective of "Waste Valorization" in modern green chemistry?

a) To burn organic waste for energy. b) To store waste in plastic containers. c) To convert organic waste into high-value organic fertilizer (biohumus).

6. SCENARIO: A correlation between high temperature (>35°C) and extremely low moisture (<40%) typically results in:

a) Faster growth of plants. b) High worm mortality and cessation of the

decomposition process. c) Optimal, high-quality biohumus.

7. Which chemical parameter is most critical to prevent "acidosis" in worms? a) High light intensity. b) Low oxygen levels. c) Stable pH levels (ideally 6.5–7.5).

8. In sustainable chemistry, what is the main advantage of using Smart IoT sensors (like an Intelligent Soil Detector)? a) It provides precise, real-time data to react to chemical fluctuations instantly. b) It eliminates the need to understand chemistry. c) It looks more professional in a laboratory.

9. What is the ideal Carbon-to-Nitrogen (C:N) ratio for efficient vermicomposting? a) 25:1 to 30:1 b) 100:1 c) 5:1

10. Why are "Capacitive" sensors preferred over "Resistive" ones in biohumus monitoring? a) They do not corrode easily in wet, chemical environments. b) They measure sunlight. c) They are smaller and cheaper

Laboratory Worksheet ***Appendix 4***

Name / Surname: _____ Group: (Control / Experimental)

Date: _____

Objective: Measure the biochemical parameters of three different soil/biohumus samples and determine their suitability for vermicomposting based on Green Chemistry principles.

PART 1: DATA COLLECTION

Instructions: Use your provided tools (Thermometer + pH strips OR Intelligent Soil Detector) to measure the parameters in all three containers. Record your data below.

Parameters	**Container A**	**Container B**	**Container C**
Temperature (°C)			
Moisture (%)			
pH Level			

PART 2: DATA ANALYSIS & COMPREHENSION (Problem Solving)

Instructions: Based on your measurements and theoretical knowledge of Chemical Technology, answer the following questions.

1. Identify the Optimal Environment:

Which container represents the most favorable environment for earthworm survival and organic decomposition? Justify your answer using the data you collected.

Answer:

_____

---

2. Chemical Imbalance Analysis (Container B):

Look at the data for Container B. What specific parameter is out of the normal range? What would happen to the microbial activity and earthworms if left in this state? How can you fix it?

Answer:

_____

---

3. pH Neutralization (Container C):

Container C shows an abnormal pH level. Is it acidic or alkaline? In industrial vermicomposting, what causes this chemical shift, and what specific materials (based on green chemistry) would you add to neutralize the soil?

Answer:

_____

PART 3: CONCLUSION

Briefly describe how confident you are in your measurements today. Did your measuring tool help you quickly understand the chemical state of the soil?

Answer:

_____

🌱 *SMART VERMICOMPOSTING: QUICK REFERENCE GUIDE*

"Green Chemistry & Waste Valorization in Action" *(Based on the research by Abilbek et al., 2025)*

Welcome to the Smart Lab! Your goal today is to act as a biotechnologist. Use your **Intelligent Soil Detector** to monitor the environment. Earthworms are living chemical factories, and they need PERFECT conditions to survive.

🌍 1. THE BIG PICTURE: What are we doing?

- **Waste Valorization:** We are not just throwing garbage away. We are transforming organic waste into a highly valuable, nutrient-rich organic fertilizer called **Biohumus**.
- **The Perfect Diet (C:N Ratio):** For efficient composting, the Carbon-to-Nitrogen ratio in the soil must be balanced between **25:1 and 30:1**.

📊 2. VITAL SIGNS: Monitor These Parameters!

Use your digital sensors to get real-time, precise data. If any of these numbers are wrong, the system will fail!

🌡 TEMPERATURE

- **Ideal:** 15°C – 25°C.
- **DANGER:** If the temperature goes above **35°C**, microbial activity stops, and the worms will literally cook to death!

💧 MOISTURE (Water Level)

- **Ideal: 60% – 80%**.
- **Why?** Moisture facilitates the movement of nutrients and supports **aerobic respiration** (breathing).
- **DANGER:** If moisture drops below **40%**, the decomposition process completely stops, and worms dry out.

🧪 **pH LEVEL (Acidity / Alkalinity)**

- **Ideal: 6.5 – 7.5** (Neutral zone).
- **DANGER:** If the pH drops below 6.0, the environment becomes too acidic. This causes **"Acidosis"** — worms get chemical burns and die.

🚑 3. EMERGENCY PROTOCOLS: How to Fix a Broken System

As a chemist, if your Smart IoT sensor alerts you to a problem, you must react instantly:

- **Problem:** pH drops to 4.5 or 5.0 (Severe Acidosis).
    - **Solution:** Add a neutralizing alkaline agent! (e.g., calcium carbonate or crushed eggshells) and improve oxygen flow.
- **Problem:** High Heat (>35°C) + Low Moisture (<40%).
    - **Solution:** Add water immediately and move the bin to a cooler, shaded place to restart the biological process.

💡 **Why use Smart Sensors?** *Traditional chemistry uses slow litmus papers. Smart IoT detectors provide precise, **real-time data**, allowing you to observe and react to chemical fluctuations instantly!*

TEACHER SURVEY INSTRUMENT

Smart Technologies in Sustainable Chemistry Education

Section 1: Background Information

Q1. What is your current professional position?

☐ School chemistry teacher
☐ University lecturer / instructor
☐ Lab Assistant
☐ Senior Lecturer
☐ Associate Professor / Professor
☐ Other: _____

Q2. How many years of teaching experience do you have?

☐ Less than 2 years
☐ 2–5 years
☐ 5–10 years
☐ More than 10 years

Q3. At which academic level do you primarily deliver instruction?

☐ Pre-university education
☐ Undergraduate education (Bachelor's level)
☐ Graduate education (Master's level)
☐ Other: _____

Section 2: Smart Technologies

Q4. How frequently do you use IoT devices/sensors in your teaching?

☐ Never

☐ Rarely (1–2 times per semester)
☐ Occasionally (3–5 times per semester)
☐ Frequently (monthly)
☐ Very frequently (weekly)

Q5. How comfortable are you with data analytics platforms?

☐ Very uncomfortable

☐ Somewhat uncomfortable

☐ Neutral

☐ Comfortable

☐ Very comfortable

Q6–Q11. Please rate each statement on a scale from 1 to 5:

Scale: 1 = Strongly Disagree — 5 = Strongly Agree

Q6. Smart technologies have improved student engagement in my classes.

Scale: 1 = Strongly Disagree — 5 = Strongly Agree

Q7. Data visualization tools help students understand complex concepts better.

Scale: 1 = Strongly Disagree — 5 = Strongly Agree

Q8. Technology saves time during practical sessions.

Scale: 1 = Strongly Disagree — 5 = Strongly Agree

Q9. Digital tools improve assessment quality.

Scale: 1 = Strongly Disagree — 5 = Strongly Agree

Q10. Students develop better critical thinking skills when working with real-time data.

Scale: 1 = Strongly Disagree — 5 = Strongly Agree

Q11. I plan to continue using smart technologies in my teaching.

Scale: 1 = Strongly Disagree — 5 = Strongly Agree

Section 3: Challenges & Open-Ended Questions

Q12. What is the main challenge in implementing smart technologies in your classroom? (Select one)

☐ Lack of equipment / devices

☐ Lack of training / professional development

☐ Time constraints (curriculum pressure)

☐ Technical difficulties / unreliable internet

☐ Low digital literacy

☐ Financial constraints

☐ No challenges

Q13. What do you consider the biggest advantage of using real-time IoT sensor data compared to traditional methods?

Answer:

_____

Q14. What advice would you give to a chemistry teacher using smart IoT sensors for the first time?

Answer:

_____

Q15. Is there anything else you would like to share about the use of smart technologies in chemistry education?

Answer:

_____

Descriptive Statistics

	pre test	post test
N	72	72
Missing	0	0
Mean	2.53	7.14
Median	3.00	7.00
Standard deviation	1.06	1.55
Minimum	1	4
Maximum	5	10

	group	pre test	post test
Mean	**Control**	2.31	6.08
	Experimental	2.75	8.19
Median	**Control**	2.00	6.00
	Experimental	3.00	8.00
Standard deviation	**Control**	0.980	1.02
	Experimental	1.11	1.24
Minimum	**Control**	1	4
	Experimental	1	5
Maximum	**Control**	4	8
	Experimental	5	10

Independent Samples T-Test

		Statistic	p		Effect Size
pre test	**Mann-Whitney U**	497	0.077	Rank-biserial correlation	0.234

Note . H_a $\mu_{Control} \neq \mu_{Experimental}$

Independent Samples T-Test

		Statistic	p		Effect Size
gain score	**Mann-Whitney U**	306	<.001	Rank-biserial correlation	0.529

Note . H_a $\mu_{Control} \neq \mu_{Experimental}$

Group Statistics

	Group	N	Mean	Median	SD	SE
gain score	**Control**	36	3.78	4.00	1.20	0.200
	Experimental	36	5.44	5.50	1.76	0.294

Descriptive Statistics

	group	pre test	post test
N	**Experimental**	36	36
	Control	36	36
Missing	**Experimental**	0	0
	Control	0	0
Mean	**Experimental**	2.75	8.19
	Control	2.31	6.08
Median	**Experimental**	3.00	8.00
	Control	2.00	6.00
Std. Deviation	**Experimental**	1.11	1.24
	Control	0.980	1.02
Minimum	**Experimental**	1.00	5.00
	Control	1.00	4.00
Maximum	**Experimental**	5.00	10.0
	Control	4.00	8.00
Shapiro-Wilk W	**Experimental**	0.905	0.923
	Control	0.874	0.900
Shapiro-Wilk p	**Experimental**	0.005	0.015
	Control	<.001	0.003

Table Pre-test ***Appendix 8***

	Q1	Q2	Q3	Q4	Q5	Q6	Q7	Q8	Q9	Q10
Expert 1	3.00	5.00	3.00	3.00	5.00	2.00	5.00	2.00	5.00	2.00
Expert 2	4.00	5.00	3.00	3.00	5.00	2.00	5.00	3.00	4.00	2.00
Expert 3	4.00	5.00	3.00	3.00	5.00	2.00	5.00	4.00	5.00	2.00
Expert 4	3.00	4.00	3.00	3.00	4.00	2.00	5.00	2.00	5.00	2.00
Expert 5	3.00	5.00	2.00	2.00	5.00	2.00	5.00	2.00	5.00	2.00

Kendall's W Test Ranks

	Mean Rank
Question_1	5,00
Question_2	8,00
Question_3	3,60
Question_4	8,00
Question_5	1,90
Question_6	7,20
Question_7	8,50
Question_8	3,00
Question_9	7,90
Question_10	1,90

Test Statistics

N	5
Kendall's W[a]	,900
Chi-Square	40,518
df	9
Asymp. Sig.	,000

a. Kendall's Coefficient of Concordance

Table Post-test ***Appendix 9***

	Q1	Q2	Q3	Q4	Q5	Q6	Q7	Q8	Q9	Q10
Expert 1	4.00	4.00	5.00	4.00	2.00	4.00	5.00	2.00	3.00	3.00
Expert 2	3.00	2.00	4.00	3.00	2.00	4.00	4.00	2.00	2.00	2.00
Expert 3	4.00	3.00	5.00	3.00	3.00	4.00	5.00	3.00	2.00	3.00
Expert 4	4.00	4.00	5.00	4.00	2.00	5.00	5.00	3.00	2.00	3.00
Expert 5	3.00	3.00	5.00	4.00	2.00	5.00	5.00	3.00	3.00	2.00

Kendall's W Test Ranks

	Mean Rank
Question_1	6,20
Question_2	4,80
Question_3	9,20
Question_4	6,00
Question_5	2,30
Question_6	8,20
Question_7	9,20
Question_8	3,30
Question_9	2,70
Question_10	3,10

Test Statistics

N	5
Kendall's W[a]	,873
Chi-Square	39,272
df	9
Asymp. Sig.	,000

a. Kendall's Coefficient of Concordance

	Q1	Q2	Q3	Q4	Q5	Q6	Q7	Q8	Q9	Q10	Q11	Q12	Q13	Q14	Q15
Exp 1	4.00	2.00	5.00	5.00	2.00	5.00	3.00	5.00	2.00	2.00	3.00	4.00	5.00	2.00	5.00
Exp 2	3.00	2.00	4.00	5.00	2.00	5.00	2.00	5.00	3.00	3.00	3.00	4.00	5.00	2.00	4.00
Exp 3	4.00	2.00	5.00	4.00	3.00	5.00	3.00	4.00	3.00	2.00	3.00	4.00	4.00	2.00	5.00
Exp 4	3.00	2.00	3.00	4.00	3.00	4.00	2.00	4.00	2.00	3.00	3.00	3.00	5.00	3.00	4.00
Exp 5	5.00	3.00	5.00	5.00	4.00	5.00	2.00	5.00	3.00	4.00	2.00	4.00	5.00	2.00	5.00

Kendall's W Test Ranks

Question_1	8,80
Question_2	2,80
Question_3	11,10
Question_4	12,10
Question_5	5,00
Question_6	12,90
Question_7	3,70
Question_8	12,10
Question_9	4,30
Question_10	5,10
Question_11	5,50
Question_12	8,50
Question_13	12,60
Question_14	3,30
Question_15	12,20

N	5
Kendall's W[a]	,836
Chi-Square	58,490
df	14
Asymp. Sig.	,000

a. Kendall's Coefficient of Concordance