nature sustainability

Supplementary information

https://doi.org/10.1038/s41893-025-01598-6

# Artificial intelligence in sustainable development research

In the format provided by the authors and unedited

## Supplementary information

# Artificial Intelligence in Sustainable Development Research

Gohr, C., Rodríguez, G., Belomestnykh, S., Berg-Moelleken, D., Chauhan, N., Engler, O., Heydebreck, L. v., Hintz, M. J., Kretschmer, M., Krügermeier, C., Meinberg, J., Rau, A.-L., Schwenck, C., Aoulkadi, I., Poll, S., Frank, E., Creutzig, F., Lemke, O., Maushart, M., Pfendtner-Heise, J., Rathgens, J., & H. von Wehrden

## Content

## List of figures



## List of tables

## Additional results description

## Sample overview

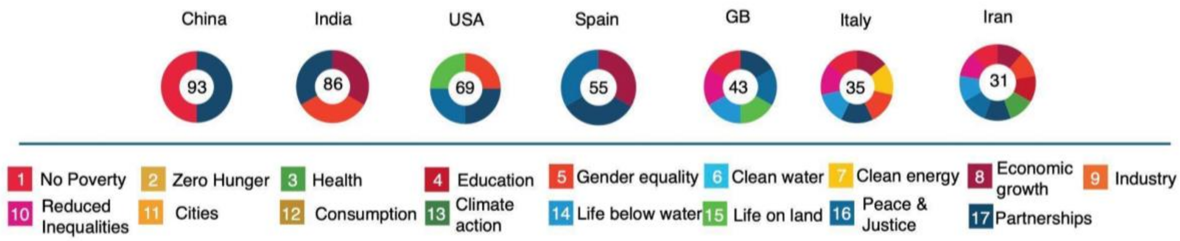


Fig. S1: The seven countries with the most articles and the corresponding SDGs that were not covered. For example, China published 93 articles related to all SDGs but SDG 1 (No poverty) and SDG 17 (Partnerships for the goals).

Most authors conduct empirical research in the country where their institution is located (Fig. S1B). In Spain, AI-powered research is applied for matters of smart farming (SDG 2, e.g. Alonso et al. 2020), smart water management (SDG 6, e.g. Ponte et al. 2016) and AI in education (SDG 4, e.g. Espinoza 2023). AI-research in China is abundant in higher education and teacher's training (SDG 4, e.g. Zu et al. 2023, Zhao et al. 2022) and in economics and clean energy (SDG 7, 8, e.g. Cao et al. 2023, Chen et al. 2020).

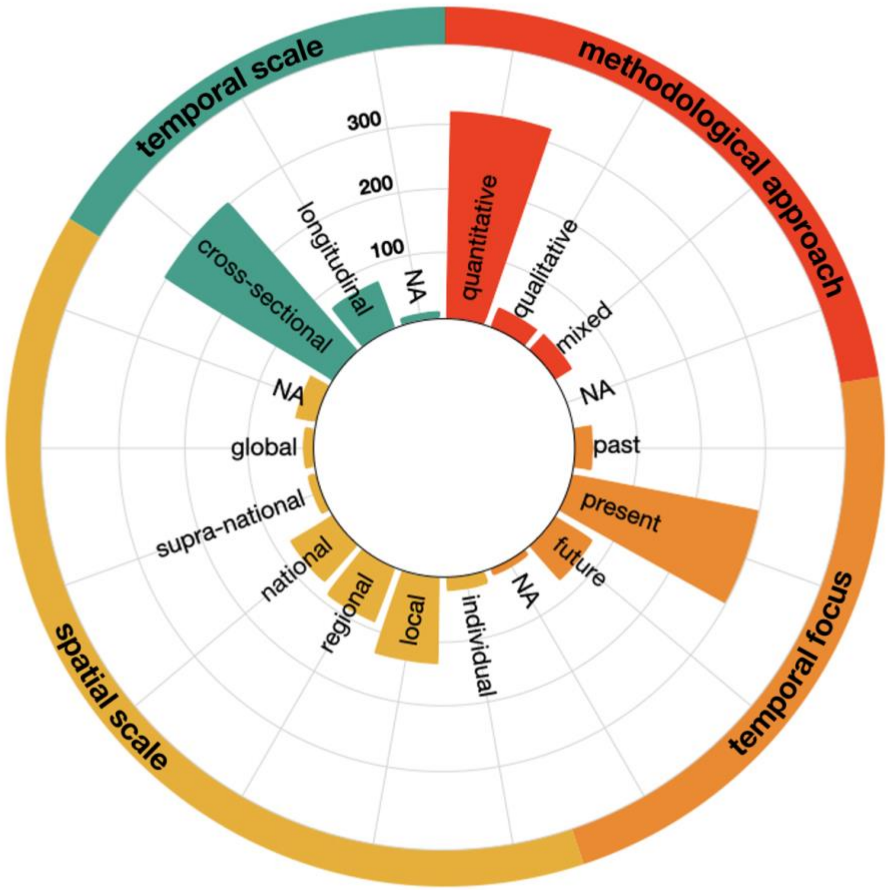


Figure S2: Methodological properties of empirical articles (n=393). The majority of empirical articles (n=393) use quantitative methods (n=330), whereas qualitative (n=27) and mixed method approaches (n=36) each make up less than 10% . Papers that analyze data from a singular point in time (n=301) dominate over those which employed a longitudinal research design (n=79). Likewise, 295 of the articles focus on the present rather than the future (n=73) or past (n=34). The focus on knowledge about the future is likely due to AI's capacity to forecast, especially since sustainability is a future-oriented concept. The spatial focus in the literature is more balanced, with emphasis being on the local (n=136), the regional (n=89) and the national level (n=77). The individual (n=23), supra-national (n=15) and global level (n=18) were less in focus.

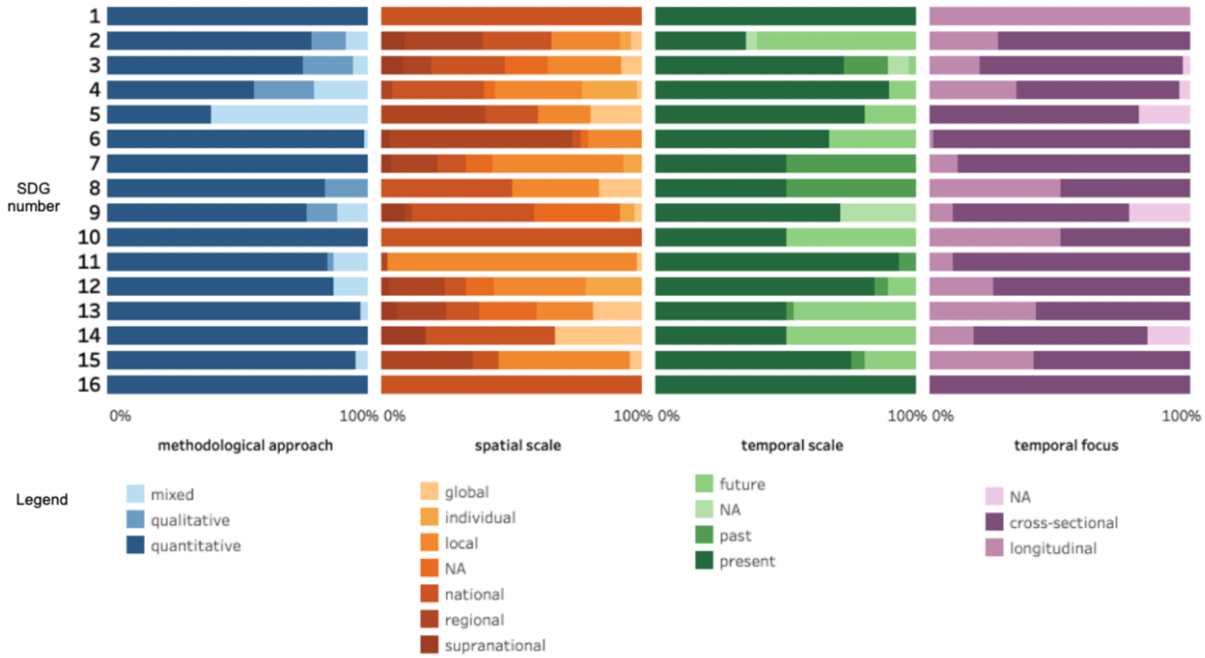


Fig. S3: Methodological properties of empirical articles (n=393) sorted by the SDGs 1-16, differentiated by the methodological approach, the spatial scale, the temporal scale and the temporal focus.

## Sustainability level analysis

The share of articles with a strong definition of sustainability was low (Fig. S5). Our focus was not on a definition of strong sustainability that we had formulated, but rather on the rigor and depth of the analysis presented in the paper. We defined levels of sustainability as strong for articles with a cited definition of sustainability and its evident application throughout the text. We defined weak sustainability for articles where a cited definition of sustainability was missing, but where sustainability or subtargets of the SDGs were mentioned in the text and the main focus of the article was for example on the application of AI without a substantial embeddedness in discussions around sustainability. The category of medium sustainability was coded, if articles mentioned sustainability or SDGs in the introduction or conclusion but did not apply frameworks or concepts in the analysis or discussion. Many studies mention SDGs as a goal that their research contributes to, yet do not investigate the corresponding 189 targets and 232 indicators.

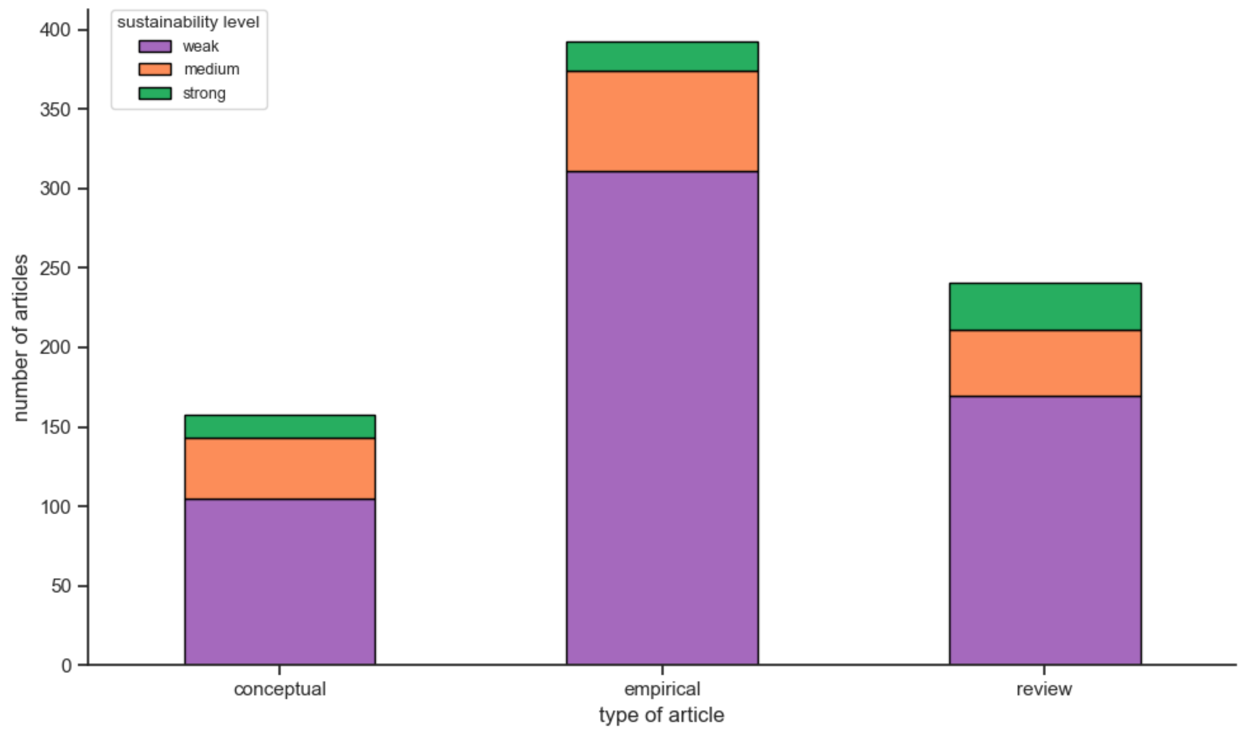


Fig. S4: Level of sustainability. Share of 792 coded articles with strong, medium or weak sustainability definition by type of article with conceptual (n=158), empirical (n=393) and review (n=241) articles.

More than half of the reviewed articles did not have a sustainability definition, indicating a significant gap in clarity and rigor within the literature. Of the remaining articles, around one third of the authors attempted to define sustainability, though these definitions varied widely in specificity. Notably, only eighty-three articles motivated their research aim with the SDGs as a whole. Fourteen studies cited the Brundtland Commission's sustainability definition. Overall, the reviewers observed little effort to define the concept of sustainability was rarely defined accurately and propose strong sustainability-related policies (Fig. S5).

Compared to the other paper types, reviews engaged most strongly within sustainability (Fig. S5). Positive examples of sustainability-driven AI research include Amiri et al. (2021) and Dauvergne (2020), each centering sustainability as a primary goal. Amiri et al. (2021) use machine learning to improve household transportation energy efficiency, aiding urban planners in reducing environmental impact. Dauvergne (2020) seeks to clarify the complexities of applying artificial intelligence to enhance sustainability in global supply chains. Both studies demonstrate a proactive engagement with sustainability, integrating it as a core consideration rather than a secondary benefit.

## Additional empirical articles analysis

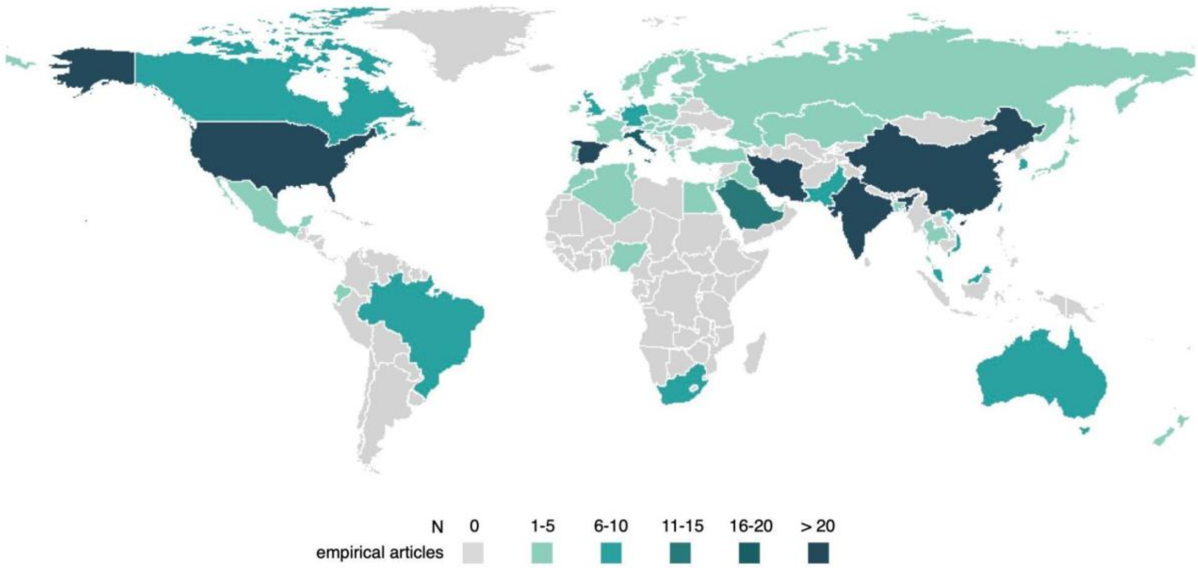


Figure S5: Map with the number of empirical articles per country (n=393). Basemap © World Food Programme, 2019. Licensed under the Open Government Licence v3.0.

## Extended description of the word analysis

The groups with the largest number of articles are *healthcare* in red with n = 62, including significant indicator words such as patient and health, *vegetation* in green with n=62 and indicators words such as forest and agriculture, and *clean energy* in green with n=60, including words such as hydrogen, demand and energy. The group *forecasting* in brown with n =49, includes words such as accuracy and prediction. On the first axis of the detrended correspondence analysis, the groups allocate left with a pattern best described as the natural sciences. Examples are here the group *water* in blue with n =53 and indicator words river, hydrology or water, and the group *vegetation*. The other end of the first axis covers the humanities. Most prominent here are the groups *education* in turquoise with n = 38 and indicator words teaching, student, thinking and the group *healthcare*. The *industry* group in violet with n=35 and indicator words such as innovation and manufacturing, is closer to the "humanities" corner than to the "natural sciences" corner. The second axis shows allocations of word groups from AI as end on top, exemplified by group *remote sensing* in olive green with n= 21 and indicator words such as detection and pixel. In the bottom word groups with AI as means, exemplified by the group *Industry* and *clean energy*.

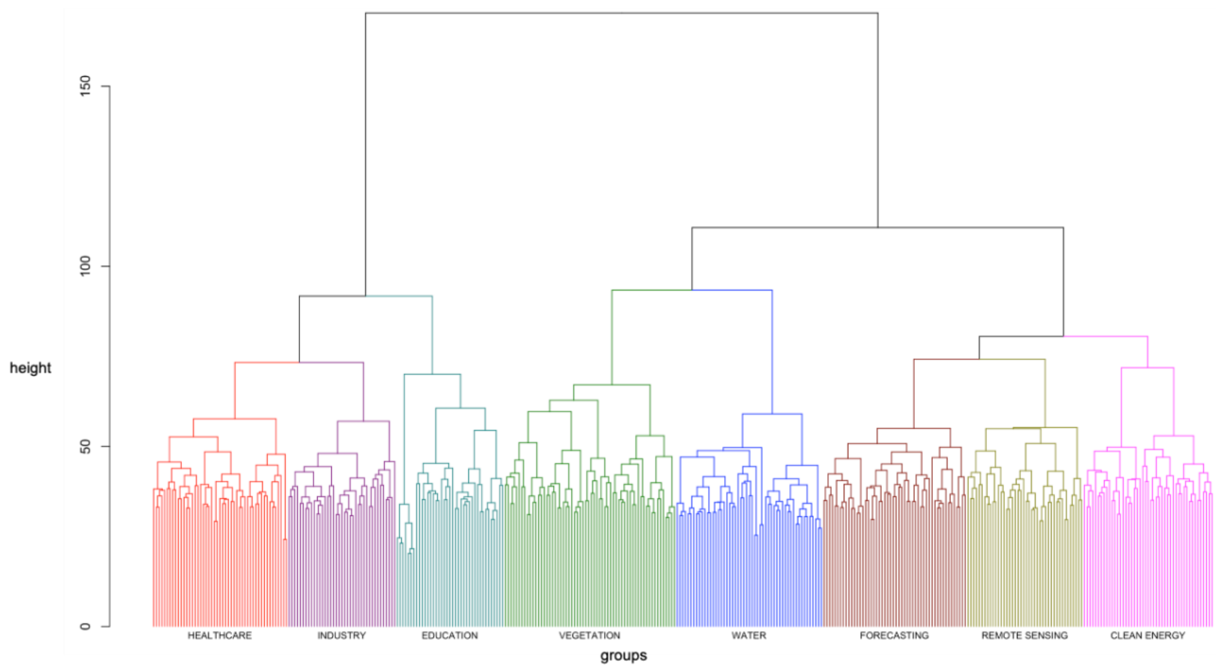


Fig. S6 Dendrogram representing the hierarchical agglomerative clustering of empirical articles (n=383) on AI for sustainable development (note: 10 articles were not considered due to overlength, for more details, see the extended methodology description).

## Role of AI

Out of the 367 papers that used quantitative or mixed methods only, we identified a focus on system optimization (208 papers), forecasting (120 papers), and data mining and remote sensing (101 papers) across all SDGs. Figure S4 illustrates that we frequently identified the role of ML for research related to certain SDGs but not for all.

For seven SDGs we identified all taxonomy roles, particularly system optimization and forecasting, suggesting a preponderant AI's role in achieving those Sustainable Development Goals (SDGs) related to process efficiency and future outcomes. (e.g., SDG 7). In contrast, data mining and remote sensing are frequently applied in social dimensions (e.g. SDG 4, SDG 11) as algorithms with this role enable the extraction of actionable insights from complex, unstructured, and large-scale data sources relevant to societal needs.

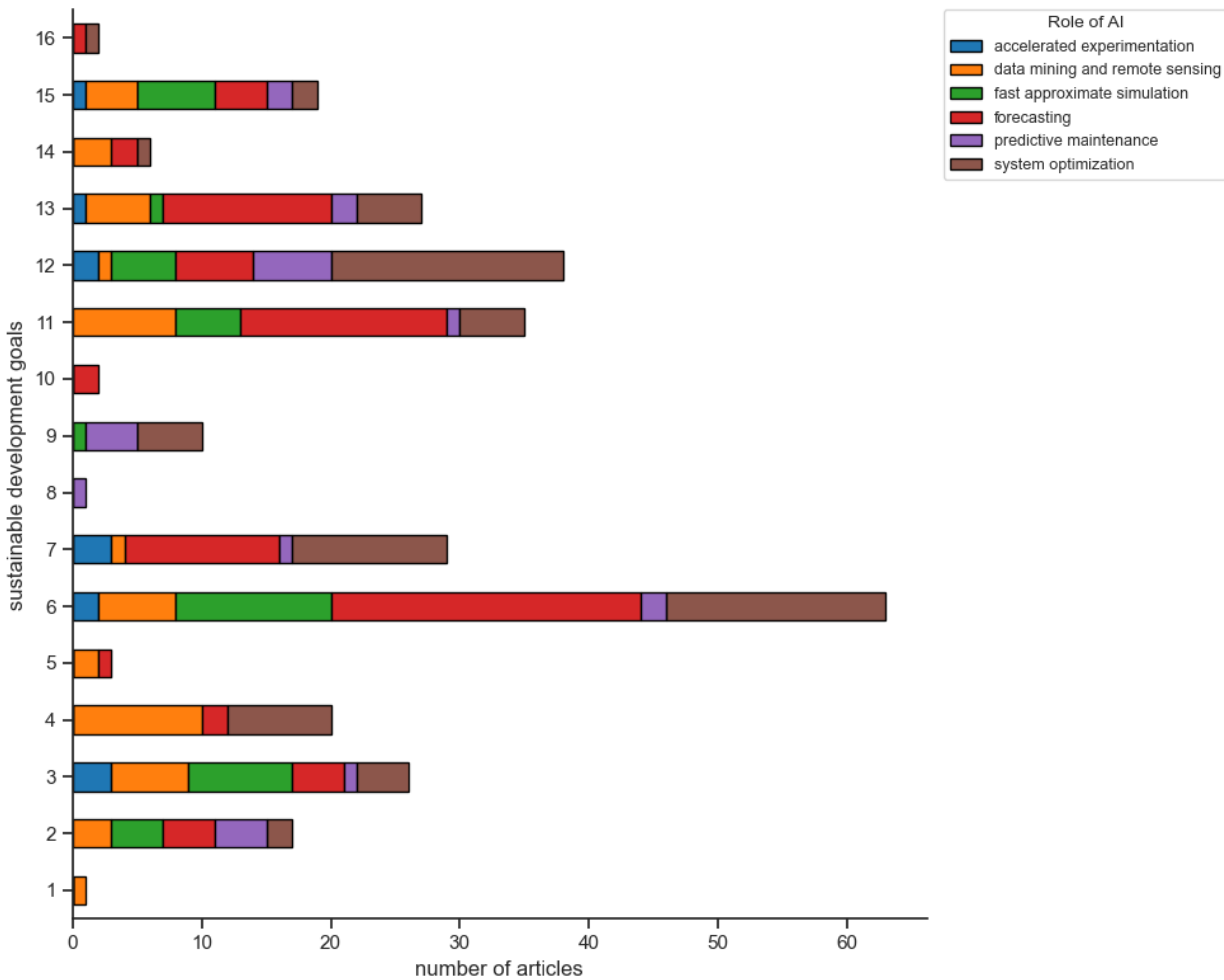


Figure S7: Six roles of AI across SDG empirical research (n=393). **Definitions** - *Accelerated experimentation*: Suggesting experiments to speed up the design process. *Data mining and remote sensing*: to translate raw data such as text documents or satellite imagery into usable insights. *Fast approximate simulation*: Rapid modeling of complex systems and processes- *Forecasting*: Predicting future events by learning from time-series data. *System optimization*: By controlling and improving the operational efficiency of complex systems to save resources and energy. *Predictive maintenance*: ML can be used in the maintenance of systems to improve efficiency, reduce costs, and build resilience.

Applying AI in educational contexts is heavily discussed and has experienced various paradigm shifts in the last 20 years (Guan et al. 2020). The field ranges from AI-supported reasoning, to adaptive learning and reflection (Zhai et al. 2021). Here again, the number of publications is increasing, with the highest output in the USA (Song & Wang 2020). This is reflected in our dataset with the USA, Spain and China being the countries with the highest share of publications addressing educational questions. Based on our cluster analysis, the group *education* of the empirical articles the majority of publications comes from China. During the screening phase, the highest proportion of true-positive articles was identified in relation to SDG 4, with a rate of 30%. This rate surpasses the average proportion of true positives found across all sub-samples by more than fourfold. In contrast, less than one percent of articles were identified as true-positives in relation to SDGs 10, 8, and 17. The high research interest and use of artificial intelligence in education spans from AI as a tool for education, its ethical implications for e.g. examination and is fueled by the appearance of large language models (Gašević et al. 2023).

## Top 10 algorithms

In our study, we identified 220 distinct algorithms. Table 1 presents the top ten most frequently applied algorithms in our sample (complete list in the appendix). The prevalence of certain algorithms in sustainability research reflects their adaptability and effectiveness in handling diverse and complex datasets essential to Sustainable Development Goals (SDGs). Neural networks (i.e., ANN, CNN, BPNN, MLP) are frequently utilized due to their robust ability to model nonlinear relationships and process high-dimensional data. Neural networks, such as BPNN, are often used for modeling and optimizing complex relationships between variables, making them effective tools for addressing multifaceted challenges in various domains. Convolutional Neural Networks (CNN) are widely utilized in classification and identification tasks, particularly in image-based systems. Algorithms like ANFIS offer a balance of interpretability and adaptability, making them well-suited for scenarios requiring human insights alongside computational modeling. Genetic algorithms, as a subset of evolutionary algorithms, excel in optimization problems, particularly when dealing with complex systems or resource constraints. LSTM networks are especially useful for analyzing time-series data, enabling accurate predictions and insights in contexts where temporal dependencies are critical, such as resource management and environmental monitoring.

Table S1: Top 10 most used algorithms in empirical research.

| Algorithm | Abbreviation | Purpose | Frequency (unique articles) | Accumulated frequency |
|---|---|---|---|---|
| Artificial neural network | ANN | Mimics the human brain to recognize patterns and relationships within data, often used for tasks like image and speech recognition. | 64 | 64 |
| Adaptive network-based fuzzy inference system | ANFIS | Combines neural networks and fuzzy logic to handle complex decision-making, useful for systems needing | 17 | 81 |

| Algorithm | Abbreviation | Purpose | Frequency (unique articles) | Accumulated frequency |
|---|---|---|---|---|
| | | adaptive and human-like reasoning. | | |
| Convolutional neural networks | CNN | Processes visual data by detecting patterns and features in images, widely used in image and video analysis. | 15 | 96 |
| Genetic algorithm | GA | Simulates natural selection to find optimal solutions by evolving through generations, useful in optimization tasks. | 13 | 109 |
| Back propagation neural network | BPNN | A learning algorithm for training neural networks by minimizing errors, commonly used in predictive tasks. | 10 | 119 |
| Multi layer perceptron | MLP | A type of neural network with multiple layers to solve complex problems, often used in classification and regression tasks. | 10 | 129 |
| Decision tree | DT | A flowchart-like model for decision-making, splitting data into branches to make predictions based on conditions. | 9 | 138 |
| Long short term memory network | LSTM | A type of recurrent neural network that remembers past information, ideal for analyzing sequential data like time series. | 9 | 147 |
| k-means | k-means | Groups similar data points into clusters, useful for finding patterns in data without labels, such as customer segmentation. | 7 | 154 |

| Algorithm | Abbreviation | Purpose | Frequency (unique articles) | Accumulated frequency |
|---|---|---|---|---|
| Extreme learning machines | - | A fast training algorithm for single-layer neural networks, effective in classification and regression with minimal adjustments. | 5 | 159 |

Overall, the findings emphasize how the choice of AI algorithms is determined by the specific demands of each identified group. Deep learning algorithms for optimization, forecasting and remote sensing dominate in vegetation, water, and clean energy. For example, Elahi et al. (2019) utilized BPNN for modeling and optimizing the complex relationships between agrochemical use, farm inputs, and rice yield efficiency; and Shreyas Madhav et al. (2022) relied on CNN algorithm for a based identification systems of electronic waste images. Algorithms like the ANFIS provide interpretability and adaptability, making them valuable for modeling systems where human input or interpretive insights are necessary, for example, Abba et al. (2020) used it to model and predict the Water Quality Index. Additionally, genetic algorithms allow for efficient optimization in challenging scenarios, like maximizing the efficiency of renewable energy layouts e.g., the optimization of energy flows in wind power generation (Chen et al. 2020). LSTM networks are crucial for time-series data, commonly found in climate change and environmental monitoring, as they effectively capture temporal dependencies, for instance, the improvement of water demand prediction for efficient distribution and management in rural areas (Ahmed et al., 2021).

## Reviews and conceptual articles analysis

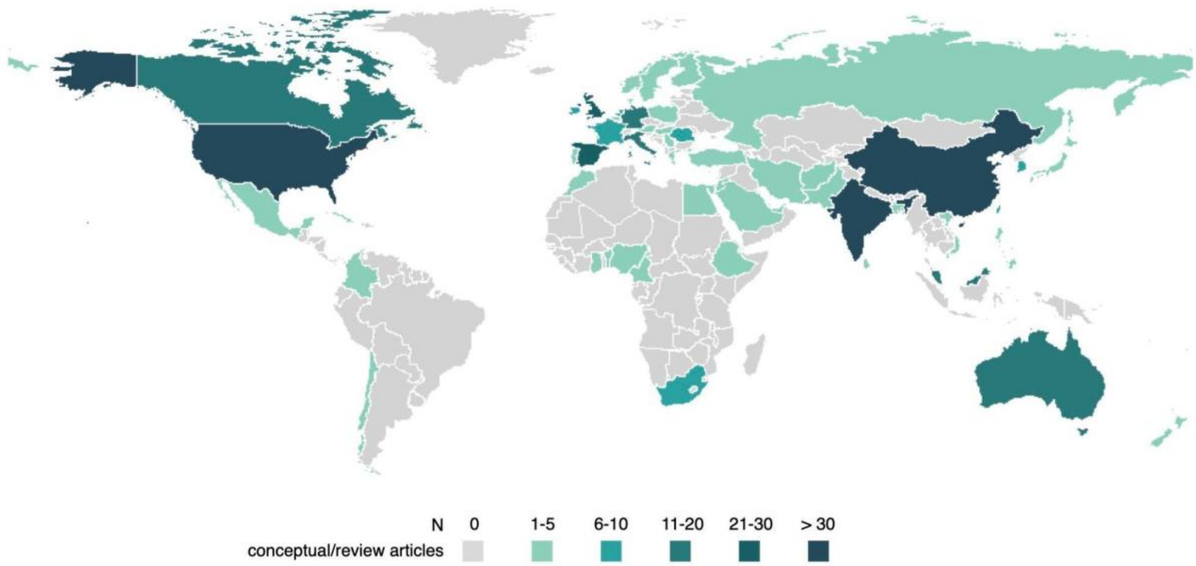


Figure S8: Map with counts per country of review and conceptual articles (n=399). There are no review/conceptual articles from Brazil, even though they published empirical articles. There is a higher share of review/conceptual articles from Australia and Canada than empirical from Australia and Canada. Basemap © World Food Programme, 2019. Licensed under the Open Government Licence v3.0.

Of the 792 articles in the full-text analysis, we classified 241 as reviews and 158 as conceptual articles. Empirical articles were dominant except for SDGs 1 - No Poverty, 2 - Zero Hunger, 7 - Affordable and Clean Energy, 10 - Reduced Inequalities, 14 - Life Below Water and 16 - Peace, Justice and Strong Institutions. Reviews were prevalent for the SDGs 1, 2, 7 and 14, whereas conceptual articles made up the largest group for SDG 16.

We identified eight groups via the multivariate full-text analysis best suitable to describe the topics addressed in the 399 identified conceptual articles and reviews (Fig. S6). The groups are *education* (74 articles), *smart farming* (78 articles), *biodiversity* (60 articles), s*mart cities* (17 articles), *clean energy* (69 articles), *healthcare* (44 articles), *waste* (16 articles), *industry* (29 articles). We excluded five articles with too many words. Similarly to the placement of articles along the first axis of the detrended correspondence analysis using the words used in the conceptual and review articles, a divide between articles working on the environment and articles working on societal matters was observed. Articles in the groups *education, healthcare and industry* used similar vocabulary. The articles range from calling for a sentient approach when discussing sustainable artificial intelligence (Bossert & Hagendorff 2023) to presenting visions for an AI-powered sustainable steel production (Colla et al. 2020). The groups *clean energy* and *waste* are isolated from the other groups and cover topics such as the framework development for a smart energy production for the African continent

(Amir & Khan 2022) or a review on the potential developments of microbial fuel cell technology (Dwivedi et al. 2022). The largest group of conceptual and review papers are articles on *smart farming*. Of the 78 articles, 52 articles were coded for SDG 2 - zero hunger. The potential of artificial intelligence in supporting agricultural management, precision farming and regenerative agriculture are among the most prominent topics (e.g. Mohamed et al. 2021, Delgado et al. 2019, McLennon et al. 2021).

## Word analysis

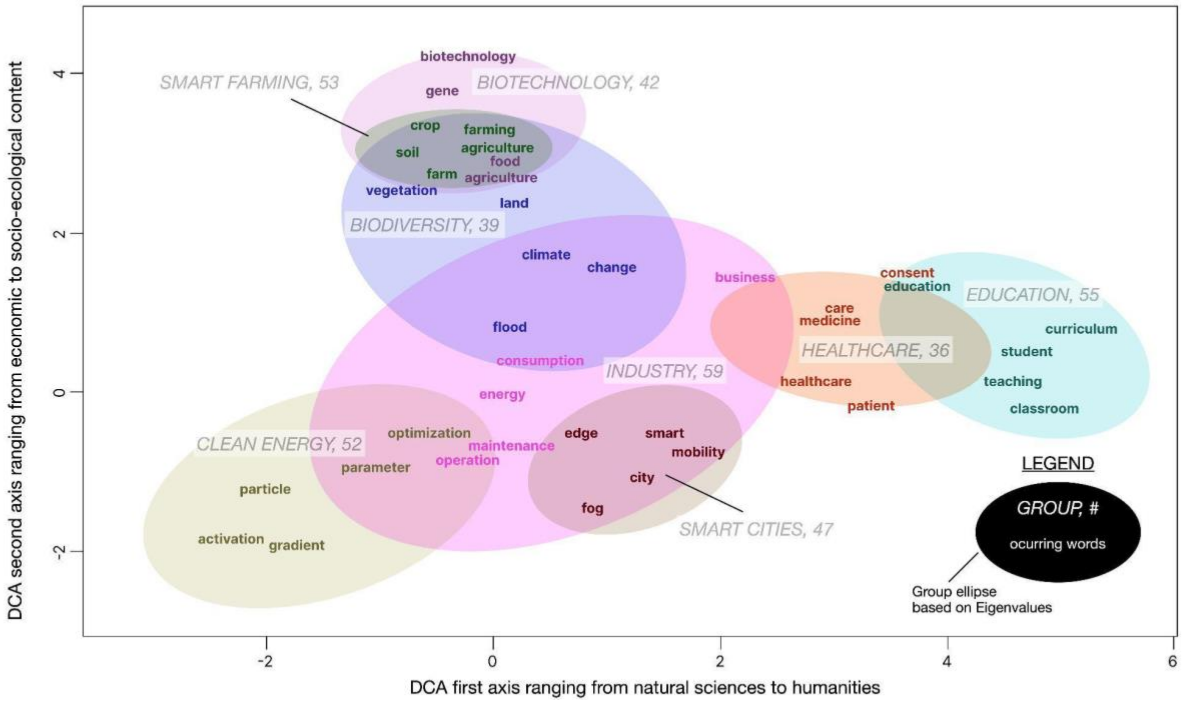


Figure S9: Research groups of 383 review and conceptual articles on AI and sustainable development. Group 1 *education* (turquoise, 55 articles), group 2 *smart farming* (green, 53 articles), group 3 *biodiversity* (blue, 39 articles), group 4 *smart cities* (beige, 47 articles), group 5 *clean energy* (olive green, 52 articles), group 6 *healthcare* (red, 36 articles), group 7 biotechnology (violet, 42 articles), group 8 *industry* (pink, 59 articles). 5 articles not part of the word cloud (outliers with e.g. too many words). To avoid artifacts in the cluster analysis due to extreme articles' length, we excluded 16 articles (see Figure S12). Group titles are based on the most abundant words per group. Axis titles are the pattern interpretation of the authors.

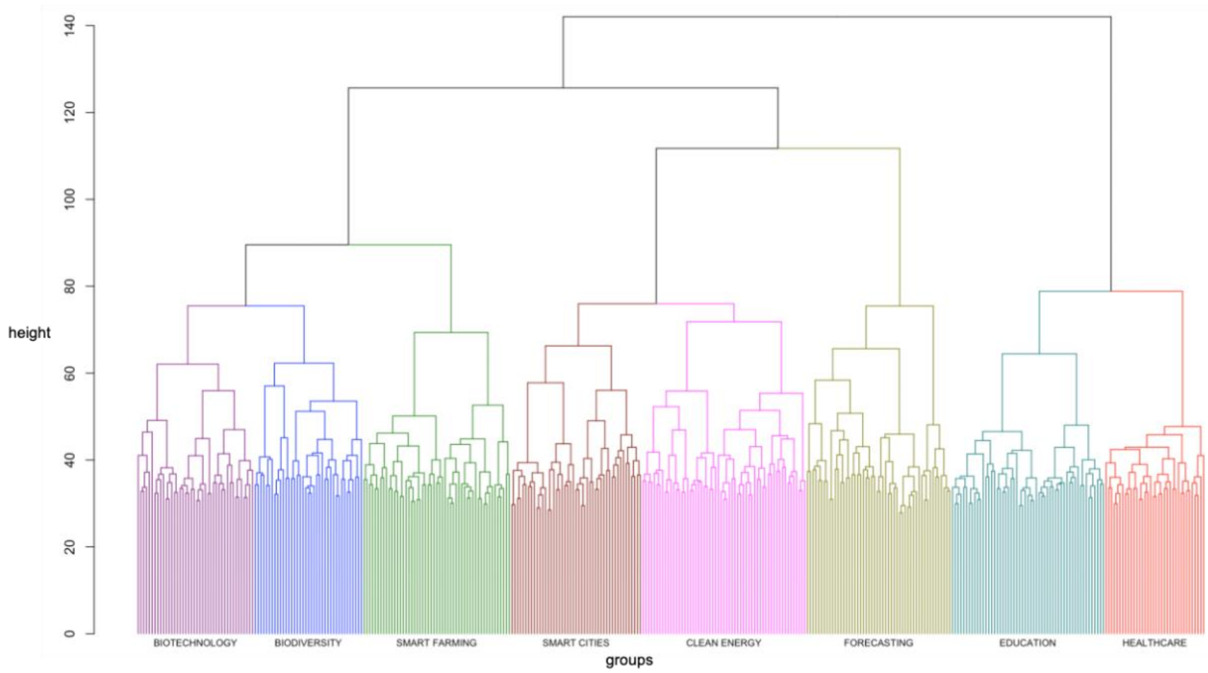


Figure S10: Dendrogram representing the hierarchical agglomerative clustering of 383 review and conceptual articles on AI for sustainable development.

## Additional methodology description

## Data filtering

Some articles like Maddikunta et al. (2022) and Jiang et al. (2021) on self-powered sensor systems and wearable electronics engage with sustainability, but their primary focus is arguably on advancing sensor and device technology rather than sustainability as a core concern. Sustainability, in these cases, is approached as a valuable by-product rather than the central driving force, with terminology serving as a backdrop to technical advancements rather than a genuine focus on long-term environmental impact. In accordance with our eligibility criteria, publications like Maddikunta et al. (2022) and Jiang et al. (2021) were excluded from the final sample.

## Words extraction

We downloaded the corresponding PDFs from our sample and imported them into Python. To partition the PDFs and extract only the main text, we utilized the “unstructured” library. This library allowed us to exclude footnotes, images, and other metadata from the extracted text. Subsequently, we employed the natural language processing library, NLTK, to perform various operations, including tokenization and POS tagging. These processes enabled us to filter out words that were not nouns. Since we believed that nouns conveyed the primary conceptual meaning, we focused on them. Additionally, NLTK’s lemmatization feature allowed us to obtain the root form of nouns, eliminating duplicates of similar nouns. Finally, we wrote the processed words into a text file for each respective article.

## Multivariate statistics words algorithm

We imported the text files into R to perform multivariate statistics to cluster the most frequent words in articles into relevant conceptual groups. However, articles with extreme low or high word counts formed artifacts: Articles with an excessive low word count lacked sufficient textual data for meaningful clustering, often forming distinct outliers. Conversely, articles with an extremely high number of words tended to cluster separately due to their greater lexical diversity. To mitigate this issue and ensure the clustering process reflected substantive abundance relationships we excluded 10 empirical and 16 conceptual/review articles that appeared as outliers in a word count boxplot (Figure S11 and S12).

After importing 8017 words from empirical articles and 9896 words from conceptual/review articles, we corrected the frequencies of words by dividing them by the total number of words in each article. For example, if the word "machine" appeared 50 times in an article with 500 words, and if the word "water" appeared 30 times in an article with 300 words, both words would be adjusted to their relative frequency, which would be 0.1 in both cases. Next, we processed the words to create an abundance table with the 20% most frequent words across all articles, resulting in 1587 words for empirical articles and 1948 words for conceptual/review articles. We then applied a logarithmic function to scale all the frequencies. Subsequently, we ran the detrended correspondence analysis (DCA) using the "vegan" library (vegetation analysis). We then used agglomerative hierarchical clustering to obtain the corresponding groups. We employed the Dufrene-Legendre Indicator Species Analysis to group the most significant abundant words. We applied the DCA axes and resulting clustering to create the plots. We iterated through different cluster numbers to determine the optimal number of clusters. The number of clusters was determined based on the abundance indicators of each group and the structure of the respective dendrograms.

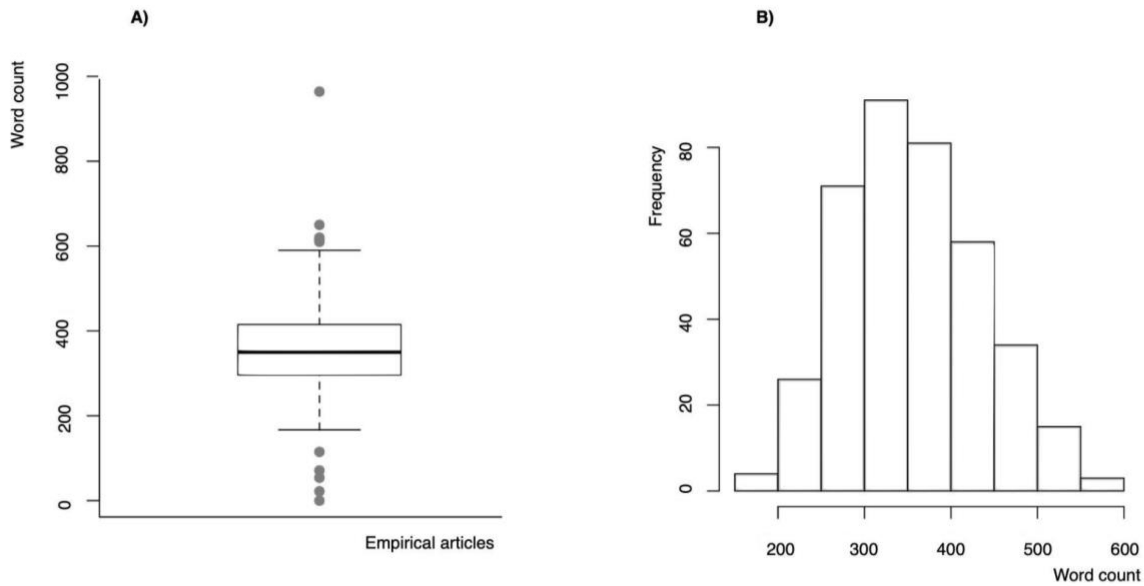


Fig S11. A) Boxplot of word count (unique nouns) of empirical articles, n=393. B) Histogram of word count of the same type of articles but with outliers removed, n=383. Outliers had a word count outside the range of 167-590.

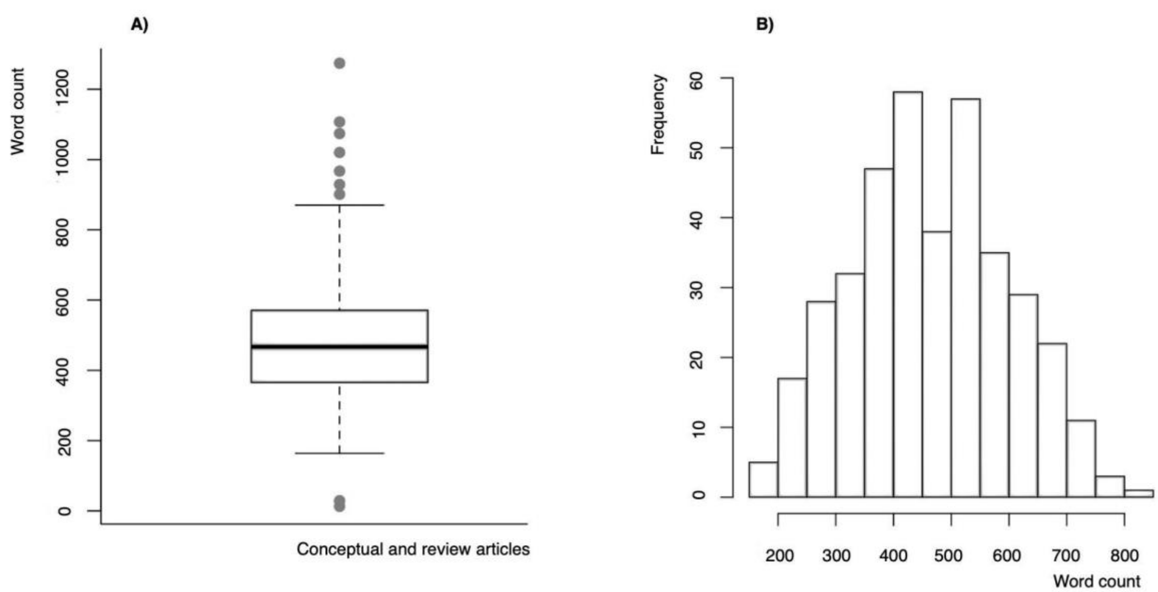


Fig S12. A) Boxplot of word count (unique nouns) of conceptual and review articles, n=399. B) Histogram of word count of the same type of articles but with outliers removed, n=383. Outliers had a word count outside the range of 164-824 words.

Table S2: Overview of steps in this literature review, including the selection of articles and steps of analyses.

| | | |
|---|---|---|
| Introduction | Database query in January 2024 with unique search strings for each of the 17 SDGs for peer-reviewed articles | |
| Identification | Total number of records identified in the Scopus database: 14423 articles | |
| Screening | Abstract screening per SDG aiming at including the 100 yearly most cited articles per SDG | Exclusion of abstracts without focus on sustainability and/or without focus on artificial intelligence and without access to full-text: 13613 |
| | Full-text records included: 792 | |
| Eligibility | Articles included in category empirical article: 393 | Articles included in the category conceptual and review articles: 399 |
| Analysis | Extracted 20% of the most frequent nouns from full-texts: empirical (n=1579), conceptual/review (n=1948) | Removed articles with overlength for empirical (n=10) and conceptual/review (n=16) |
| | Hierarchical cluster analysis and idicator species analysis leading to 8 groups of articles for empirical and conceptual/review articles respectively | |

Table S3. Search strings for the Scopus database, hits and number of included articles. The search was conducted in January 2024.

| SDG | Search string | Total Hits | Total Hits in English | Included | Included in % |
|---|---|---|---|---|---|
| 1 | TITLE-ABS-KEY ( ( "AI" OR "Artificial Intelligence*" OR "A.I." ) AND ( "poverty*" OR "social* protect*" OR ( ( "resilience" OR "vulnerab*" ) AND ( "soci*" OR "economic*" ) ) AND "sustainab*" ) ) AND PUBYEAR < 2024 AND ( LIMIT-TO ( DOCTYPE , "ar" ) OR LIMIT-TO ( DOCTYPE , "re" ) ) | 199 | 190 | 7 | 3.67% |
| 2 | TITLE-ABS-KEY ( ( "AI" OR "A.I." OR "Artificial Intelligence*" ) AND ( "hunger*" OR "food*" OR "agricultur*" OR "nutrit*" ) AND "sustainab*" ) AND PUBYEAR > 1995 AND PUBYEAR < 2024 AND ( LIMIT-TO ( DOCTYPE , "ar" ) OR LIMIT-TO ( DOCTYPE , "re" ) ) | 1016 | 976 | 90 | 9.22% |
| 3 | TITLE-ABS-KEY ( ( "AI" OR "A.I." OR "Artificial Intelligence*" ) AND ( "health" OR "disease*" OR "well-being" ) AND "sustainab*" ) AND PUBYEAR < 2024 AND ( LIMIT-TO ( DOCTYPE , "ar" ) OR LIMIT-TO ( DOCTYPE , "re" ) ) | 1101 | 1051 | 95 | 9.03% |
| 4 | TITLE-ABS-KEY ( ( "AI" OR "A.I." OR "Artificial Intelligence*" ) AND ( "education*" OR "literacy" OR "numeracy" ) AND "sustainab*" AND NOT "health" ) AND PUBYEAR > 1996 AND PUBYEAR < 2024 AND ( LIMIT-TO ( DOCTYPE , "ar" ) OR LIMIT-TO ( DOCTYPE , "re" ) ) | 342 | 326 | 91 | 27.91% |
| 5 | TITLE-ABS-KEY ( ( "AI" OR "Artificial Intelligence*" OR "A.I." ) AND ( "gender" OR "wom*" OR "girl*" ) AND "sustainab*" ) AND PUBYEAR > 1995 AND PUBYEAR < 2024 AND ( LIMIT-TO ( DOCTYPE , "ar" ) OR LIMIT-TO ( DOCTYPE , "re" ) ) | 63 | 57 | 8 | 2.81% |
| 6 | TITLE-ABS-KEY (( "AI" OR "A.I." OR "Artificial Intelligence" ) AND ( "sanitation" OR "water*") AND "sustainab*" ) AND PUBYEAR > 1995 AND PUBYEAR < 2024 AND ( LIMIT-TO ( DOCTYPE , "ar" ) OR LIMIT-TO ( DOCTYPE , "re" ) ) | 851 | 820 | 89 | 14.03% |
| 7 | TITLE-ABS-KEY ( ( "ai" OR "artificial intelligence*" OR "a.i." ) AND "energy*" AND "sustainab*" ) AND PUBYEAR > 2003 AND PUBYEAR < 2024 AND ( LIMIT-TO ( DOCTYPE , "ar" ) OR LIMIT-TO ( DOCTYPE , "re" ) ) | 1368 | 1337 | 71 | 5.31% |
| 8 | TITLE-ABS-KEY ( ( "AI" OR "A.I." OR "Artificial Intelligence*" ) AND ( "work" OR "economic growth" OR "gdp" OR "employment" OR "labour" ) AND "sustainab*" ) AND PUBYEAR > 1995 AND PUBYEAR < 2024 AND ( LIMIT-TO ( DOCTYPE , "ar" ) OR LIMIT-TO ( DOCTYPE , "re" ) ) | 1265 | 1214 | 10 | 0.82% |

Table S3. Search strings for the Scopus database, hits and number of included articles. The search was conducted in January 2024.

| SDG | Search string | Total Hits | Total Hits in English | Included | Included in % |
|---|---|---|---|---|---|
| 9 | TITLE-ABS-KEY ( ( ( "AI" OR "A.I." OR "Artificial Intelligence*" ) AND ( "industr*" OR "infrastructur*" OR "innovati*" ) AND "sustainab*" ) ) AND PUBYEAR > 1994 AND PUBYEAR < 2024 AND ( LIMIT-TO ( DOCTYPE , "ar" ) OR LIMIT-TO ( DOCTYPE , "re" ) ) | 2587 | 2543 | 55 | 2.16% |
| 10 | TITLE-ABS-KEY ( ( "AI" OR "A.I." OR "Artificial Intelligence*" ) AND ( "equal*" OR "inequal*" OR "income" OR "developing country" ) AND "sustainab*" ) AND ( LIMIT-TO ( DOCTYPE , "ar" ) OR LIMIT-TO ( DOCTYPE , "re" ) ) | 619 | 600 | 5 | 0.83% |
| 11 | TITLE-ABS-KEY ( ( ( "AI" OR "A.I." OR "Artificial Intelligence*" ) AND ( "urban*" OR "city*" OR "cities*" OR "municipal*" OR "district*" OR "settlement*" OR "resident*" ) AND "sustainab*" ) ) AND PUBYEAR > 1993 AND PUBYEAR < 2024 AND ( LIMIT-TO ( DOCTYPE , "ar" ) OR LIMIT-TO ( DOCTYPE , "re" ) ) | 1075 | 1055 | 86 | 8.15% |
| 12 | TITLE-ABS-KEY ( ( "AI" OR "A.I." OR "Artificial Intelligence*" ) AND ( "consumption*" OR "production*" ) AND "sustainab*" ) AND ( LIMIT-TO ( DOCTYPE , "ar" ) OR LIMIT-TO ( DOCTYPE , "re" ) ) | 2935 | 2817 | 68 | 2.41% |
| 13 | TITLE-ABS-KEY ( ( "AI" OR "A.I." OR "Artificial Intelligence*" ) AND ( "climate change" OR "climate action" ) AND "Sustainab*" ) AND PUBYEAR < 2024 AND ( LIMIT-TO ( DOCTYPE , "ar" ) OR LIMIT-TO ( DOCTYPE , "re" ) ) | 469 | 447 | 62 | 13.87% |
| 14 | TITLE-ABS-KEY ( ( "AI" OR "A.I." OR "Artificial Intelligence*" ) AND ( "marin* system*" OR "fish*" OR "coast*" OR "ocean*" ) AND "sustainab*" ) AND PUBYEAR > 1999 AND PUBYEAR < 2024 AND ( LIMIT-TO ( DOCTYPE, "ar" ) OR LIMIT-TO ( DOCTYPE, "re" ) ) | 177 | 164 | 18 | 10.98% |
| 15 | TITLE-ABS-KEY ( ( "AI" OR "Artificial intelligence*" OR "A.I." ) AND ( "Conservation*" OR "biodiv*" OR "ecosystem" OR "species" ) AND "sustainab*" ) AND PUBYEAR < 2024 AND ( LIMIT-TO ( DOCTYPE , "ar" ) OR LIMIT-TO ( DOCTYPE , "re" ) ) | 871 | 830 | 25 | 3.01% |
| 16 | TITLE-ABS-KEY ( ( ( "AI" OR "A.I." OR "Artificial Intelligence*" ) AND ( "peace" OR "justice" OR "institution" ) AND "sustainab*" ) ) AND PUBYEAR < 2024 AND ( LIMIT-TO ( DOCTYPE , "ar" ) OR LIMIT-TO ( DOCTYPE , "re" ) ) | 232 | 220 | 12 | 5.45% |

Table S3. Search strings for the Scopus database, hits and number of included articles. The search was conducted in January 2024.

| SDG | Search string | Total Hits | Total Hits in English | Included | Included in % |
|---|---|---|---|---|---|
| 17 | TITLE-ABS-KEY ( ( "AI" OR "A.I." OR "Artificial Intelligence*" ) AND ( "implementation" OR "partnership*" OR "development aid" OR "financial support" OR "financial assistance" OR "developing countries" OR "developed countries" OR "global north" OR "global south" OR "trade" ) AND "sustainab*" ) AND NOT "trade-offs" AND ( LIMIT-TO ( DOCTYPE , "ar" ) OR LIMIT-TO ( DOCTYPE , "re" ) ) | 1012 | - | 0 | 0% |

Table S4. Number of articles with more than 30 citations from 2018 to 2023 for each SDG.

| | | Year Published | | | | | |
|---|---|---|---|---|---|---|---|
| **SDG** | **SDG Name** | **2018** | **2019** | **2020** | **2021** | **2022** | **2023** |
| 1 | No Poverty | | | | 1 | | |
| 2 | Zero Hunger | | 3 | 10 | 11 | 1 | 2 |
| 3 | Good Health and Well Being | 1 | 4 | 12 | 7 | 4 | |
| 4 | Quality Education | 2 | | | 2 | 1 | 2 |
| 6 | Clean Water and Sanitation | 3 | 3 | 9 | 8 | 2 | |
| 7 | Affordable and Clean Energy | | 2 | 6 | 10 | 8 | 2 |
| 8 | Decent Work and Economic Growth | | | 1 | 2 | | |
| 9 | Industry, Innovation and Infrastructure | | 1 | 3 | 8 | 5 | |
| 10 | Reduced Inequalities | | | 1 | | | |
| 11 | Sustainable Cities and Communities | 4 | 7 | 15 | 20 | 7 | 1 |
| 12 | Responsible Production and Production | 5 | 8 | 3 | 12 | 6 | 2 |
| 13 | Climate Action | | 1 | 2 | 2 | 5 | 1 |
| 14 | Life Below Water | | | | 2 | 2 | |
| 15 | Life on Land | | | | | | 1 |
| 16 | Peace Justice and Strong Institutions | | | | 1 | | |

| | | | | | | |
|---|---|---|---|---|---|---|
| Total | 15 | 29 | 62 | 86 | 41 | 11 |

Table S5. Articles from 2023 with more than 30 citations (sorted by number of citations).

| In text citation | Title | SDG | Number of Citations |
|---|---|---|---|
| Kooli 2023 | Chatbots in Education and Research: A Critical Examination of Ethical Implications and Solutions | 4 | 87 |
| Cao et al. 2023 | Multidiscipline Applications of Triboelectric Nanogenerators for the Intelligent Era of Internet of Things | 7 | 49 |
| Khan et al. 2023 | Applications of machine learning in thermochemical conversion of biomass-A review | 7 | 46 |
| Sridhar et al. 2023 | Global impact of COVID-19 on agriculture: role of sustainable agriculture and digital farming | 15 | 44 |
| Holzinger et al. 2023 | AI for life: Trends in artificial intelligence for biotechnology | 2 | 42 |
| Cowls et al 2023 | The AI gambit: leveraging artificial intelligence to combat climate change—opportunities, challenges, and recommendations | 13 | 39 |
| Snitiala et al. 2023 | Macro-nutrients recovery from liquid waste as a sustainable resource for production of recovered mineral fertilizer: Uncovering alternative options to sustain global food security cost-effectively | 2 | 38 |
| Son et al. 2023 | Algorithmic urban planning for smart and sustainable development: Systematic review of the literature | 11 | 35 |
| Farghali et al. 2023 | Strategies to save energy in the context of the energy crisis: a review | 12 | 34 |
| Akkem et al. 2023 | Smart farming using artificial intelligence: A review | 12 | 34 |

| | | | |
|---|---|---|---|
| Flores Vivar, Garcia Peñalvo 2023 | Reflections on the ethics, potential, and challenges of artificial intelligence in the framework of quality education (SDG4); [Reflexiones sobre la ética, potencialidades y retos de la Inteligencia Artificial en el marco de la Educación de Calidad (ODS4)] | 4 | 33 |

Table S6: Coding scheme for the investigated research articles.

| Category | Description | Code |
|---|---|---|
| **AI** | *Inclusion/exclusion criterion*: Does the article focus on AI? | yes(1)/no(0) |
| **Sustainability** | *Inclusion/exclusion criterion*: Does the article focus on the SDGs/sustainability? | yes(1)/no(0) |
| **AI for what** | | |
| **Core topic** | *Inductive*: What is the core topic of the article? | text snippets, e.g. water quality monitoring, smart courts, health-care decision making |
| **Role of AI** | *Deductive*: What is the role of AI? (based on Kaack et al. 2022) | Data mining and remote sensing/Accelerated experimentation/Fast approximate simulation/Forecasting/System optimization/Predictive maintenance |
| **Means/End** | *Deductive*: Is AI used or operationalised as a "means" (AI for sustainability) or as an "end" (sustainability of AI)? | means(1)/end(2): e.g. smart irrigation systems (means), carbon emissions of AI algorithms (end) |
| **AI how** | | |
| **Type of AI** | *Inductive*: What type of AI is used or discussed? | text snippets, e.g. GPS, SAR, cadaster, smart meters |
| **Algorithms used** | *Inductive*: Which algorithm is used or discussed? | text snippets, e.g. GPT, LR, SVM, DNN |
| **Method/Study object** | *Deductive*: Is AI a method and/or the study object? | method(1)/study object(2): e.g. AI for personalized learning (method), analysis of AI implementation in healthcare (study object) |
| **AI as buzzword** | *Deductive*: Is the term AI used as a buzzword in the article? | yes(1)/no(0) |
| **Sustainability** | | |

| | | |
|---|---|---|
| **Sustainability definition** | *Inductive*: What definition of/reference for sustainability is given? | text snippets, e.g. Brundtland, Three Pillars, SDGs, intergenerational justice |
| **Level of sustainability** | *Deductive*: What is the level of sustainability?<br>**weak sustainability**: mentions sustainab* or subtargets of the SDG frequently in the text; there's seems to be a link to sustainability, but it's not logically derived. **medium sustainability**: mentions SDG(x) or highlights otherwise the connection between AI and sustainability in the SDG via addressing the subtargets but analysis does not focus on it, so rather a pretext (buzzword, marketing). **strong sustainability**: provides a cited sustainability definition and this becomes evident in the research | weak/medium/strong |
| **Type of paper** | *Deductive*: What is the type of paper? | empirical/conceptual/review |
| | ***For empirical papers*** | |
| **Spatial scale** | *Deductive/inductive*: What is the study's spatial scale? | individual/local/regional/national/ supranational/international/global |
| **Temporal scale** | *Deductive*: What is the study's timeframe? | crosssectional/longitudinal study |
| **Temporal scale** | *Deductive*: What is the article's temporal focus? | past/present/future |
| **Methods** | *Deductive*: Which methods are used? | qualitative/quantitative/mixed methods |
| **Type of data** | *Inductive*: What type of data was used in the study? | text snippets, e.g. weather data, field experiment data, remote sensing data, Internet text data |
| **Location of the study (country)** | *Inductive*: Where did the study take place? | text snippets, e.g. Singapore, Morocco, Oman |
| **Country of first author** | *Inductive*: In which country is the first author affiliated to an institution? | text snippets, e.g. Taiwan, India, Mexico |
| **Policy recommendations** | *Deductive*: Is there an own dedicated subsection for policy recommendations? | yes(1)/no(0) |

Table S7: Description of word analysis groups for empirical papers and the covered SDGs.

| Group | Color | Number of articles | top 10 words | Top 3 Sdgs | Top 3 algorithms | Recommended readings |
|---|---|---|---|---|---|---|
| **1 - Healthcare** | red | 49 | care, health, healthcare, patient, hospital, privacy, adoption, society, access, medicine | 3, 4, 11 | Artificial Neural Network, Convolutional Neural Network, Random Forest | Bellantuono et al. 2022 |
| | Most articles in this group was fetched from the search strings of SDG 3 (n=22), SDG 4 (n=11) and SDG 11 (n=10). The Covid pandemic brought studies using AI e.g. to report on telehealth to deciding with a chatbot about triage or discussing proximity tracing technologies on smartphones. In other studies, AI again in form of chatbots was investigated to understand the use for health coaching, self-education. | | | | | |
| **2 - Vegetation** | green | 62 | soil, vegetation, land, crop, conservation, cover, agriculture, area, water, slope | 2, 6, 15 | Artificial Neural Network, Adaptive Network-based Fuzzy Inference System, Back Propagation Neural Network | Huang et al. 2023 |
| | The majority of articles in this group was fetched from the search strings of SDG 15 (n=15), SDG 2 (n=15) and SDG 6 (n=14). Studies found for the SDG 15 use AI-based approaches for ecological monitoring such as land use change, pollination services, risk of forest loss with the aim to develop policy recommendations for sustainable forest management or economic development. Articles coded for SDG 2 focus on improving systems for sustainable food production such as smart greenhouse production or genetic resources analysis. The articles coded for SDG 6 use AI-based algorithms to model and predict streamflows, evapotranspiration, water quality. | | | | | |

| Group | Color | Number of articles | top 10 words | Top 3 Sdgs | Top 3 algorithms | Recommended readings |
|---|---|---|---|---|---|---|
| **3 - Forecasting** | brown | 52 | vector, feature, accuracy, prediction, forecasting, input, parameter, weather, algorithm, electricity | 3, 7, 12 | Artificial Neural Network, Convolutional Neural Network, Long Short Term Memory Network | Ajagekar et al. 2023, Chakraborty et al. 2021 |
| | Most articles in this group was fetched from the search strings of SDG 7 (n=13) and SDG 12 (n=10). Most articles were published in the last three years. Several studies propose and apply AI-based approaches to monitor and optimize renewable energy. Related articles, yet fetched under SDG 12, purpose AI-based system optimization for sustainable production. This word group suggests that research topics of SDG 7 and 12 are intertwined. | | | | | |
| **4 - Water** | neon blue | 53 | river, rainfall, hydrology, water, square, basin, evaporation, forecasting, reservoir, runoff | 6, 7, 11 | Artificial Neural Network, Adaptive Network-based Fuzzy Inference System, Back Propagation Neural Network | Palani et al. 2008, Egbueri et al. 2023 |
| | Most articles in this group was fetched from the search strings of SDG 6 (n=42). The articles use AI-based algorithms to model and predict streamflows, evapotranspiration, water quality. | | | | | |
| **5 - Remote sensing** | olive green | 47 | camera, detection, device, transmission, architecture, sensor, server, edge, image, cloud | 11, 12, 13 | Artificial Neural Network, Convolutional Neural Network, Back Propagation Neural Network | Mbani et al. 2022 |
| | In this group, no SDG was dominant. Shares range from 1 to 4 articles per SDG. The studies in this group range from AI-based processing of hyperspectral data for grassland classification or processing of optical underwater images for seafloor classification to deep learning and of Google Street view images for tree species detection. | | | | | |

| Group | Color | Number of articles | top 10 words | Top 3 Sdgs | Top 3 algorithms | Recommended readings |
|---|---|---|---|---|---|---|
| **6 - Clean energy** | pink | 42 | fuel, energy, hydrogen, gas, emission, carbon, design, generation, heat, building | 7, 12, 13 | Artificial Neural Network, Genetic Algorithm, Adaptive Network-based Fuzzy Inference System | Anđelković et al. 2020, Ghadami et al. 2021 |
| | Most articles in this group was fetched from the search strings of SDG 11 (n=15), SDG 12 (n=15) and SDG 7 (n=11). There is a thematic overlap between SDG 7 (clean energy), SDG 11 (sustainable cities) and SDG 12 (climate change). Research topics cover modeling effects of hybridization for energy sources, improving waste management, process optimization for biodiesel production, addressing scheduling problems in manufacturing systems and developments for green batteries. The studies of SDG 11 in this group address smart cities from different angles. Investigations range from battery life or smart charging stations for electric vehicles over AI-enhanced traffic monitoring to smart homes and the internet of things. | | | | | |
| **7 - Industry** | violet | 39 | manufacturing, chain, competitiveness, business, market, industry, customer, productivity, innovation, product | 9, 12, 13 | Artificial Neural Network, Genetic Algorithm, Support Vector Machine | Bag et al. 2021, Bildirici et al. 2023 |
| | Most articles in this group were fetched from the search string of SDG 9 (n=22). A major study focus in this group is the enhancement of different (sustainable) supply chains supported by blockchain-based smart contracts or big data analytics. | | | | | |
| **8 - Education** | turquoise | 39 | teaching, curriculum, student, teacher, education, classroom, course, instruction, school, university | 4, 8, 9 | Artificial Neural Network, Convolutional Neural Network, Decision Tree | Luo et al. 2023 |
| | Most articles in this group were fetched from the search string of SDG 4 (n=36). Articles in this group discuss and analyze the challenges and potential of AI for early-stage education and higher education. Foci are media and digital literacy, ChatGPT and ethical challenges related to artificial intelligence. | | | | | |

## References


Ajagekar, A. & You, F. Machine learning for uncovering hidden opportunities in high-performance simulation of sustainable systems. ACS Sustainable Chemistry & Engineering 11, 3362–3371 (2023).

Alonso, R. S., Sittón-Candanedo, I., García, Ó., Prieto, J., & Rodríguez-González, S. An intelligent Edge-IoT platform for monitoring livestock and crops in a dairy farming scenario. Ad Hoc Networks 98, 102047 (2020).

Amir, M., & Khan, S. Z. Assessment of renewable energy: Status, challenges, COVID-19 impacts, opportunities, and sustainable energy solutions in Africa. Energy and Built Environment 3, 348–362 (2022).

Amiri, S. S., Mottahedi, S., Lee, E. R., & Hoque, S. Peeking inside the black-box: Explainable machine learning applied to household transportation energy consumption. Computers Environment and Urban Systems 88, 101647 (2021).

Anđelković, A. S., & Bajatović, D. Integration of weather forecast and artificial intelligence for a short-term city-scale natural gas consumption prediction. *Journal of Cleaner Production*, *266*, 122096 (2020).

Bag, S., Pretorius, J. H. C., Gupta, S., & Dwivedi, Y. K. Role of institutional pressures and resources in the adoption of big data analytics powered artificial intelligence, sustainable manufacturing practices and circular economy capabilities. *Technological Forecasting and Social Change*, *163*, 120420 (2021).

Bellantuono, L., Monaco, A., Amoroso, N., Lacalamita, A., Pantaleo, E., Tangaro, S. & Bellotti, R. Worldwide impact of lifestyle predictors of dementia prevalence: An eXplainable Artificial Intelligence analysis. Frontiers in Big Data 5, 1027783 (2022).

Bildirici, M., & Ersin, Ö. Ö. Nexus between Industry 4.0 and environmental sustainability: A Fourier panel bootstrap cointegration and causality analysis. *Journal of Cleaner Production*, *386*, 135786 (2023).

Bossert, L. N., & Hagendorff, T. The ethics of sustainable AI: Why animals (should) matter for a sustainable use of AI. Sustainable development 31, 3459–3467 (2023).

Cao, X., Xiong, Y., Sun, J., Xie, X., Sun, Q., & Wang, Z. L. Multidiscipline applications of triboelectric nanogenerators for the intelligent era of internet of things. Nano-Micro Letters 15, 14 (2023).

Chakraborty, D., Alam, A., Chaudhuri, S., Başağaoğlu, H., Sulbaran, T. & Langar, S. Scenario-based prediction of climate change impacts on building cooling energy consumption with explainable artificial intelligence. Applied Energy 291, 116807 (2021).

Colla, V., Pietrosanti, C., Malfa, E., & Peters, K. Environment 4.0: How digitalization and machine learning can improve the environmental footprint of the steel production processes. Matériaux & Techniques 108, 507 (2020).

Dauvergne, P. Is artificial intelligence greening global supply chains? Exposing the political economy of environmental costs. Review of International Political Economy 29, 696–718 (2020).

Delgado, J. A., Short Jr, N. M., Roberts, D. P., & Vandenberg, B. Big data analysis for sustainable agriculture on a geospatial cloud framework. Frontiers in Sustainable Food Systems 3, 54 (2019).

Du, J., Liu, Y., Xu, Z., Duan, H., Zhuang, M., Hu, Y., ... & Fu, B. Global effects of progress towards Sustainable Development Goals on subjective well-being. Nature Sustainability 7, 360–367 (2024).

Dwivedi, K. A., Huang, S. J., & Wang, C. T. Integration of various technology-based approaches for enhancing the performance of microbial fuel cell technology: A review. Chemosphere 287, 132248 (2022).

Egbueri, J. C., Unigwe, C. O., Agbasi, J. C., & Nwazelibe, V. E. Indexical and artificial neural network modeling of the quality, corrosiveness, and encrustation potential of groundwater in industrialized metropolises, Southeast Nigeria. *Environment, development and sustainability*, *25*(12), 14753-14783 (2023).

Espinosa, Á. V., Lendínez, A. M., Melguizo, F. J., & Estévez, M. E. Engineering and Technology Education in University Studies: Driving Digital, Sustainable, and Resilient Development—A Case Study in Andalusia, Spain. IEEE Access 11, 108967–108981 (2023).

Fire, M., & Guestrin, C. Over-optimization of academic publishing metrics: observing Goodhart's Law in action. GigaScience 8, giz053 (2019).

Gašević, D., Siemens, G., & Sadiq, S. Empowering learners for the age of artificial intelligence. Computers and Education: Artificial Intelligence 4, 100130 (2023).

Ghadami, N., Gheibi, M., Kian, Z., Faramarz, M. G., Naghedi, R., Eftekhari, M., ... & Tian, G. Implementation of solar energy in smart cities using an integration of artificial neural network, photovoltaic system and classical Delphi methods. *Sustainable Cities and Society*, *74*, 103149 (2021).

Guan, C., Mou, J., & Jiang, Z. Artificial intelligence innovation in education: A twenty-year data-driven historical analysis. International Journal of Innovation Studies 4, 134–147 (2020).

Huang, H., Chen, K., Zhang, H., & Ren, L. Planning and coordinated response mechanism of economic and ecological services in urban expansion. *Economic research-Ekonomska istraživanja*, *36*(1), 2400-2420 (2023).

Jiang, M., Lu, Y., Zhu, Z., & Jia, W. Advances in Smart Sensing and Medical Electronics by Self-Powered Sensors Based on Triboelectric Nanogenerators. Micromachines 12, 698 (2021).

Li, C., & Zhou, H. Enhancing the Efficiency of Massive Online Learning by Integrating Intelligent Analysis into MOOCs with an Application to Education of Sustainability. Sustainability 10, 468 (2018).

Luo, W., He, H., Liu, J., Berson, I. R., Berson, M. J., Zhou, Y., & Li, H. Aladdin's Genie or Pandora's Box for early childhood education? Experts chat on the roles, challenges, and developments of ChatGPT. *Early Education and Development*, *35*(1), 96-113 (2024).

Maddikunta, P. K. R., Pham, Q., Nguyen, D. C., Huynh-The, T., Aouedi, O., Yenduri, G., Bhattacharya, S., & Gadekallu, T. R. Incentive techniques for the Internet of Things: A survey. Journal of Network and Computer Applications 206, 103464 (2022).

Mbani, B., Schoening, T., Gazis, I. Z., Koch, R., & Greinert, J. Implementation of an automated workflow for image-based seafloor classification with examples from manganese-nodule covered seabed areas in the Central Pacific Ocean. *Scientific Reports*, *12*(1), 15338 (2022).

McLennon, E., Dari, B., Jha, G., Sihi, D., & Kankarla, V. Regenerative agriculture and integrative permaculture for sustainable and technology driven global food production and security. Agronomy Journal 113, 4541–4559 (2021).

Mohamed, E. S., Belal, A. A., Abd-Elmabod, S. K., El-Shirbeny, M. A., Gad, A., & Zahran, M. B. Smart farming for improving agricultural management. The Egyptian Journal of Remote Sensing and Space Science 24, 971–981 (2021).

Our World in Data team. "SDG Tracker: Measuring progress towards the Sustainable Development Goals" Published online at OurWorldinData.org. Retrieved from: 'https://ourworldindata.org/sdgs' [Online Resource] (2023).

Palani, S., Liong, S. Y., & Tkalich, P. An ANN application for water quality forecasting. *Marine pollution bulletin*, *56*(9), 1586-1597 (2008).

Ponte, B., De la Fuente, D., Parreño, J., & Pino, R. Intelligent decision support system for real-time water demand management. International Journal of Computational Intelligence Systems 9, 168–183 (2016).

Zhai, X., Chu, X., Chai, C. S., Jong, M. S. Y., Istenic, A., Spector, M., ... & Li, Y. A Review of Artificial Intelligence (AI) in Education from 2010 to 2020. Complexity 2021, 8812542 (2021).

Zhao, L., Wu, X., & Luo, H. Developing AI literacy for primary and middle school teachers in China: based on a structural equation modeling analysis. Sustainability 14, 14549 (2022).

Zhu, Z., & Zhang, L. Artificial Intelligence Empowers Postgraduate Education Ecologically Sustainable Development Model Construction. Sustainability 15, 6157 (2023).