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Towards an IoT-Enabled Digital Earth for SDGs: The Data Quality Challenge

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ABSTRACT Digital Earth (DE), a technology offering real-time visualisation of Earth's processes, has shown promising results in aiding decision-making for a sustainable world, raising awareness about individual impacts on our planet, and supporting the United Nations Sustainable Development Goals (UN SDGs) agenda. However, both DE and SDGs face a common obstacle: Data Quality (DQ). This review investigates the challenge of DQ in the context of DE for SDGs and explores how IoT can address this challenge and extend the reach of DE to support SDGs. Furthermore, the study discusses three core aspects; first, the potential of IoT as a data source that supplements satellite data for DE for SDGs, second, the DQ challenge that is specific to an IoT-enabled DE for SDGs illustrated through scenarios identified from the literature, and third, solutions and perspectives that address the DQ challenge. This study underscores the necessity of addressing the DQ challenge and discusses some potential solutions to foster effective interdisciplinary collaboration, knowledge sharing, and data reusability. The study provides a viewpoint for understanding and addressing the DQ challenge for an IoT-enabled DE for SDGs to support the UN SDGs agenda for a sustainable world by 2030.

INDEX TERMS Digital earth, data quality, environmental monitoring, internet of things, sustainable development goals.

I. INTRODUCTION

With the historic adoption of the Sustainable Development Goals (SDGs) [1], the global community acknowledged the significance of the year 2015 as a transition point in addressing the pressing and unparalleled worldwide issues that were shaping the twenty-first-century landscape [2]. As of 2023, halfway through the UN 2030 Agenda for a Sustainable World, SDGs continue to struggle to support the agenda for a sustainable world [3], [4], [5], [6]. The inability of member states to invest in statistical offices and promote SDGs progress reporting has led to the unavailability and inconsistency of geospatial data to inform decision-making [7], [8]. The twenty-first-century world faces unparalleled challenges, including climate change, natural disasters, resource depletion, pandemics, and socio-economic crises that are worse than ever before [9], [10], [11].

Digital Earth (DE), a technology introduced in [12] that can visualise the environmental processes of our planet in real-time, addresses the immediate need to understand the complex processes taking place within the Earth system by offering knowledge visualisation in real-time using geospatial data to inform decision-making for a better sustainable world [3], [13]. DE also addresses the need to inform the public about humankind's impacts on the Earth as a system by providing a visualisation of socio-economic and environmental actions [14] for a common global struggle for a better world. Various DE applications have also shown promising results in contributing towards achieving SDGs ranging from poverty control [15] to climate change [16] and contributing to achieving sustainable cities and communities [17]. Although various studies have outlined DE capabilities to support sustainable development and its common synergy with SDGs, both DE and SDGs in general and DE for SDGs in particular continue to face a common challenge: *Data Quality* (*DQ*) [18], [19]. DQ remains a major obstacle in achieving the full potential of DE and the SDGs [20], [21], [22]. DQ is described as the suitability of data to the objectives of the analysis [23], [24], the level to which a set of essential attributes fulfil the requirement [25], [26] as well as how well data complements the demands of its users [27].

Technical concepts like Essential Variables (EVs) offer a holistic approach to capture the diverse aspects of Earth System, particularly of global sustainability, and efficiently describe socio-ecological systems, serving as a bridge between vast and heterogeneous datasets that help connect data with indicators [28], [29]. Essential Climate Variables (ECVs), Essential Biodiversity Variables (EBVs), and Essential Water Variables (EWVs) are examples of some of the essential EVs used for SDG monitoring [17]. A set of Essential SDGs Variables (ESDGVs) have been used for DE implementation in [17] to tackle the DQ challenge [30]. However, EVs are developed using data from diverse sources [31]. This gives rise to concerns surrounding the validity, accessibility, and traceability of data and whether the data used in the EVs is thoroughly validated with negligible (or zero) human errors [32]. When diverse environmental data is gathered and handled, data consistency remains a difficult feat to achieve [33]. Satellite data has contributed significantly to achieving DE for SDGs vision because of its availability at large scales across time and space [34], [35], [36], [37]. However, users also face data inconsistency, giving rise to a DQ challenge, when data is required at a finer granular (or detailed) level at a particular location where data from satellites often leads to mismatches in temporal and spatial scales [38]. With this requirement for more fine-grained geospatial data, the Internet of Things (IoT) emerged as a critical component capable of addressing the ever-growing data requirements at a fine granular level, enabling data-driven decision-making, complementing the satellite data to enhance its consistency, quality, and granularity, and extending the reach of DE to create a *system of systems* that particularly supports SDGs and their implementation monitoring [39], [40], [41].

While IoT can enhance overall geospatial DQ by providing frequent data at a finer level [42], [43], it also adds its own (additional) DQ challenge [44], [45], [46]. This review aims to delve into the DQ challenge arising from an IoT-enabled DE for SDGs. This study has formalised and acknowledged various data challenges as DQ issues and has identified various DQ dimensions that affect the process of data sharing. This study has also proposed a *system of systems* which may address the DQ challenge. The DQ challenge hinders effective collaboration, knowledge sharing, and data reusability across diverse interdisciplinary fields. Hence, identifying and addressing this DQ challenge is of importance. The data discussed throughout this study pertains exclusively to geospatial data. To reach our aims, we intend to review literature and undertake a discussion based on the study themes outlined in Table 1.

TABLE 1. **Study themes and their motivations.**

Study Theme	Motivation
The DQ Challenge in IoT	To provide context as well as awareness on various forms of the DQ challenge existing within IoT.
IoT's potential to become a data source for DE and SDGs in the presence of satellite data	To provide context on the DQ challenge faced by satellite data to support DE for SDGs vision. Furthermore, to present an idea and potential solution using IoT to overcome the DQ challenges associated with satellite data, resulting in facilitating the implementation of DE for SDGs.
DQ challenge in an IoT-enabled DE for SDGs	To highlight and provide awareness of the DQ challenge arising from the potential solution to complement satellite data i.e., an IoT-enabled DE for SDGs.
Solutions and perspectives for DQ challenge in an IoT-enabled DE for SDGs and Earth Sciences	To highlight and provide awareness as well as context of techniques that are being used to tackle the DQ challenge arising from complementing satellite data through IoT as well as IoT-enabled DE for SDGs.

Based on the above-mentioned study themes in Table 1, first, we discuss in section two the DQ data challenge faced by SDGs. Section three discusses and sheds light on defining DQ, DQ dimensions, and DQ dimensions in IoT. Section four discusses DE and its concept for the global good. Section five highlights the potential of IoT in overcoming the DQ challenge faced by DE for SDGs. Subsequently, in section six, we highlight the DQ issues arising at the intersection of an IoT-enabled DE for SDGs. Moreover, section seven discusses solutions to the DQ challenge and perspectives within the Earth sciences domain identified through the literature reviewed, and finally, in section eight, the study is concluded.

II. Data Quality in Sustainable Development Goals Data

Findings from the Voluntary National Reviews (VNRs) process [8], [47], [48] unveiled a recurring issue, particularly in developing countries: the lack of *suitable data* (or *fit-for-purpose data*) to populate the SDGs indicators. Many countries, particularly developing ones, grapple with inadequacies in their statistical institutions, governance structures, data quality, and time series availability [49]. This often results in significant variations in data collection (DQ dimensions *Accuracy*, *Granularity*, *Completeness*, *Timeliness*) and presentation methodologies (DQ dimensions *Consistency*, *Format*, *Interpretability*, *Ease of Understanding*) over time and across regions [50], [51], hindering the access to *suitable* or *fit-for-purpose data*. DQ and DQ dimensions will be defined in detail in the following section. Global stakeholders are encountering the same challenge in achieving SDGs as they faced during the early stages of the Millennium Development Goals (MDGs)

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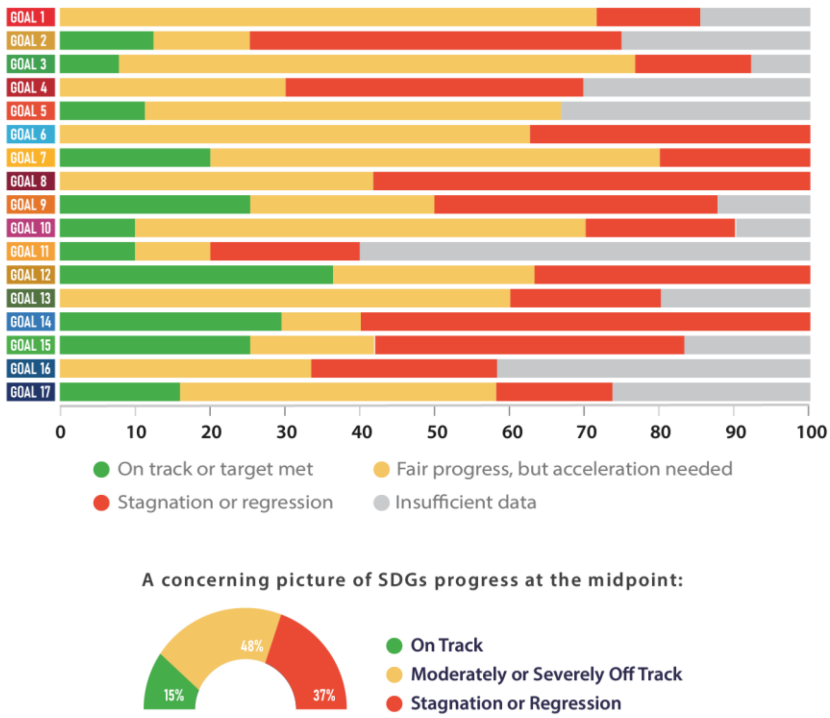

FIGURE 1. **SDGs Progress 2023 [52].**

[53], [54]: a dearth of data quality for effective monitoring and implementation [8], [14], [55].

The United Nations in its '*The Sustainable Development Goals 2023 Repor*t' [52] presents a comprehensive report on the state of SDGs – how they started to show promising results in their early years, and where they stand as of today. According to this report, an evaluation of approximately 140 progress monitoring targets (*https://unstats.un.org/sdgs/indicators/indicators-list*), for which there is accessible trend data, reveals that roughly half of these targets are experiencing significant deviations from the intended trajectory as can be seen in Figure 1. Furthermore, over 30 percent of these targets have either shown no progress or have regressed below the baseline established in 2015. The cumulative impact of factors such as climate issues, deficient decision-making, and economic disparities is leaving many developing countries with limited avenues and even fewer resources to transform the SDGs into tangible outcomes. The lack of data consistency (DQ dimensions *Consistency*, *Availability*, *Completeness*, *Trustworthiness*, *Validity*) remains a great obstacle to achieving tangible outcomes through effective decision-making [56], [57] as shown in Figure 1 (*available global data and analysis can be accessed at: https://unstats.un.org/sdgs/dataportal/*).

Figure 1 provides a very simple yet worrying visualisation of the DQ challenge faced by SDGs. Although the insufficient data problem varies for each SDG as seen in Figure 1, it is a reality for almost all the SDGs, particularly for those that require quantitative data. For instance, Sustainable Cities and Communities (SDG-11) which is pivotal to the enhancement of socio-economic development across the globe, is facing an alarming challenge because of insufficient data to decide (or act) upon. At this stage, one might ponder the substantial data being generated globally across various sectors and wonder why it remains underutilised. But the real question should be whether this data is *suitable* and *fit-for-purpose* (e.g., consistent) to complement SDGs transparently. This is the question that we will try to answer through this study. Having discussed the DQ challenge in the context of SDGs and before going into the details of whether the data, particularly in the Earth sciences domain, is *suitable* or *fit-for-purpose*, we define DQ as well as its dimensions in the context of IoT in the next section.

III. Data Quality, Data Quality in Internet of Things, and Data Quality Dimensions in Internet of Things

Data is the raw, unprocessed, and unstructured material that represents observations and/or facts, whereas information is the processed and structured form of data that provides context and meaning [58]. DQ is described as the suitability of data to the objectives of the analysis [23], [24], the level to which a set of essential attributes fulfil the requirement [25], [26] as well as how well data complements the demands of its users [27]. Furthermore, in an IoT-specific context, DQ refers to how suitable the collected data from smart things is

TABLE 2. **IoT DQ Dimensions [59].**

DQ Dimension	Definition
Accuracy	The extent to which data exhibits attributes that reflect the genuine value of the intended characteristic of a concept or occurrence within a specified context of application [60].
Availability	The accessibility and readiness of data whenever it's needed for analysis, processing, or decision-making [61].
Believability	The extent to which data is seen as reliable, truthful, and trustworthy [62].
Currency	Currency refers to how users personally assess or perceive how current or up-to-date information is [63].
Completeness	Completeness in an information a system means the information system has enough data to function properly and deliver accurate results. This involves ensuring it includes all the crucial details. [64].
Confidence	It refers to data's reliability based on measures of accuracy, correctness, and representativeness [65].
Ease of Understanding	Measures how quickly and intuitively user can grasp the meaning of the data without needing deep analysis [66].
Ease of Access	Ease of Access measures how readily and quickly a user can locate and obtain the data they need [67].
Format	Refers to the way data is organised and presented which influences how users perceive its reliability and usefulness [68].
Frequency (temporal resolution)	Frequency refers to the time periods between data acquisition, recording, and/or updates[69].
Granularity	Granularity refers to the level of detail within the data, ranging from aggregated summaries to individual points [65].
Interpretability	Interpretability reflects how clearly and effectively data is presented, using appropriate language, symbols, and units [70].
Objectivity	The degree to which data remains neutral and avoids internal or external biases, maintaining impartiality [70].
Privacy	The degree of measures taken to safeguard confidentiality and prevent unauthorised access, collection, use of data [71].
Reputation	Reputation reflects the perceived trustworthiness and value of data, influenced by its source and the information it contains [70].
Relevance	The significance and meaningfulness of collected data in alignment with the intended purpose and objectives of the system [70].
Security	How well access to data is controlled and limited to avoid any unauthorised access [70].
Timeliness	Timeliness refers to how current or recent the data is in relation to what is needed for a specific task [72].
Trustworthiness	Trustworthiness pertains to the reliability, authenticity, and credibility of the data being collected, processed, and transmitted [65].
Usability	Usability refers to the attribute of commonly acknowledged information and data models that enable expressing data in a connected and meaningful way to ensure data is more compatible across different systems and simpler to use, resulting in higher-quality data [73].
Validity	The degree to which the data accurately represents or corresponds to the real-world objects, events, or conditions it is intended to describe or measure [74].
Volume (Throughput)	A measure of the quantity or size of data generated, transmitted, processed, or stored within an IoT system over a specific period [75].

[76]. Smart things are any objects and/or devices that incorporate technology, sensors, and connectivity to enhance their functioning [77]. The diversity of the data sources and the volume of data collected from these smart things result in new difficulties in the DQ field, hence it is important to consider that practitioners and researchers aim to assess the fitness for use of their data sets [78], [79]. DQ criteria, also known as DQ Dimensions, are used to measure fitness for the use of data [80]. These DQ dimensions include, for example, *Accuracy*, *Timeliness*, *Accessibility*, and *Reliability* [81]. As our discussion in this study surrounds the DQ challenge in an IoT-enabled DE for SDGs, it is important to first identify DQ dimensions in the context of IoT. Mansouri et al. [59] conducted a systematic review and identified a

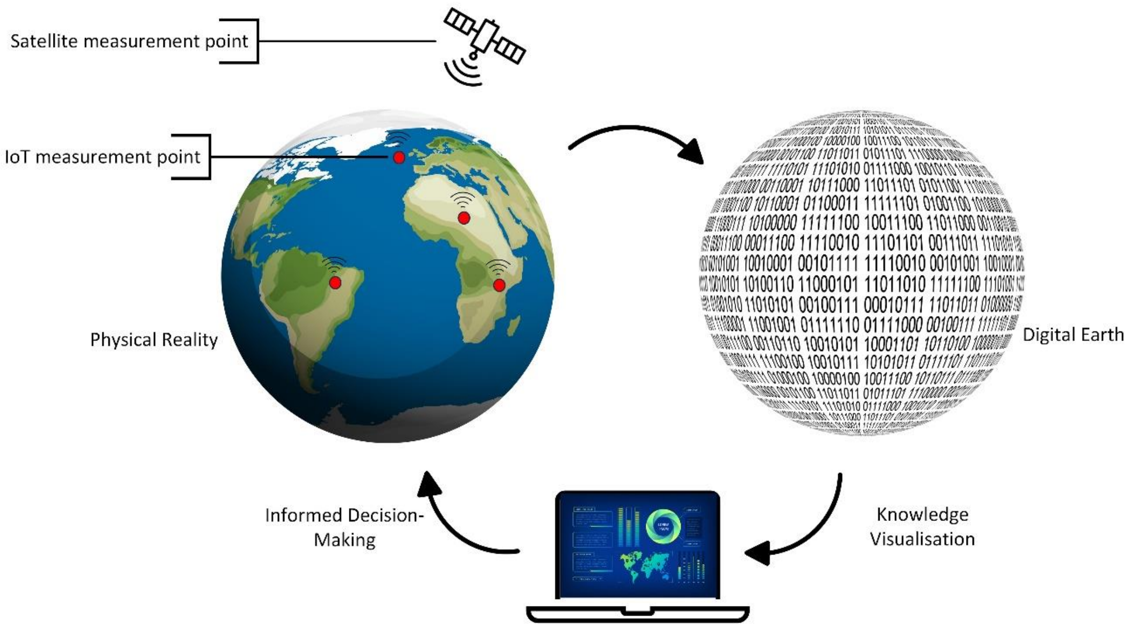

FIGURE 2. **The DE concept for the global good through knowledge visualisation for efficient decision-making.**

comprehensive list of DQ dimensions in IoT as shown in Table 2. To increase the understanding of these DQ dimensions in IoT, we have added definitions of these DQ dimensions in Table 2 that were identified from the literature reviewed during this study. Although some of the DQ dimensions outlined in Table 2 may need a human review for for evaluation, some are quantitative (or computable) in nature, for instance, *Volume*, *Frequency*, and *Timeliness* [82]. These quantitative DQ dimensions tend to complement the qualitative DQ.

DQ dimensions, for instance, the DQ dimension *Accuracy* complements *Believability* and *Confidence* [73]. IoT data, which is quantitative in nature, is also complemented by qualitative data [83]. DQ dimensions *Accuracy*, *Completeness*, *Format*, *Timeliness*, *Believability*, and *Interpretability* collectively contribute to the overall assessment of data consistency (DQ dimension *Consistency*) [84] which is crucial to enable information and knowledge sharing [85], particularly in a *system of systems* (e.g., an IoT-enabled DE for SDGs) where semantic interoperability is highly important for knowledge exchange [86]. Having defined what data and information are previously, it would be beneficial for readers to also know what knowledge is. Knowledge is the understanding and/or comprehension of information incorporating experience and insights [58]. These concepts form a hierarchical progression, where data serves as the foundation for information, and information, in turn, provides the basis for knowledge [87]. The DQ dimensions identified and defined in Table 2 will be useful as we will refer to these throughout the study while discussing various DQ issues, particularly in the scenarios identified from the literature which are discussed later in section six. In our next section, we describe DE, a technology that can enhance decision-making and complement SDGs, in the light of the reviewed literature.

IV. Digital Earth for Sustainable Development Goals

DE can be described as a digital representation of our planet, offering a layered dataset with numerous dimensions and applications that are accessible to the public [13], [88]. DE functions as a digital framework aiming to enhance our collective interpretation and understanding of the intricate relationship between humankind and the environment, ultimately beneficial for the global good [18], [89], [90]. Additionally, it embodies the ambitious concept of a Digital Twin, combining (including but not limited to) the geological, atmospheric, hydrological, biological, and thermodynamic characteristics of Earth with various socio-economic, political, and environmental aspects [91], [92]. This concept of DE supports the SDGs agenda as it plays a crucial role in bridging and connecting the physical as well as virtual realities of our world, with the overarching objective of enhancing the understanding and management of humankind's impact on socio-economic, environmental, and economic aspects by allowing a deeper interpretation of global and local dynamics [93], [94], [95], as illustrated in Figure 2.

As seen in Figure 2, data acquired through satellite and IoT feeds into the DE from physical reality where knowledge generation, environmental monitoring, hazard mitigation, and informed decision-making take place through real-time 'what

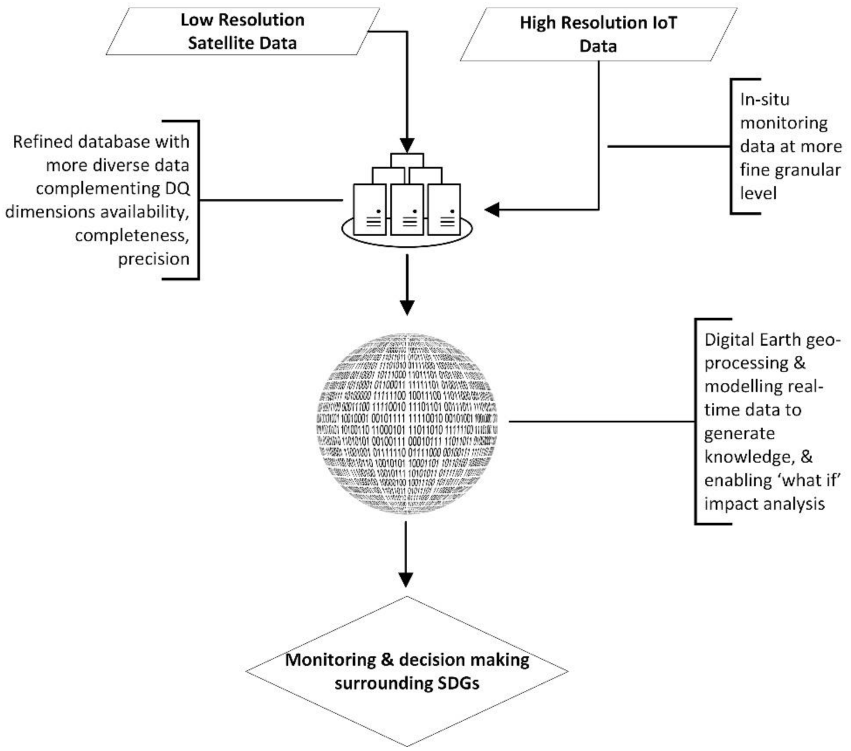

FIGURE 3. **An IoT-enabled DE for SDGs where IoT complements the satellite data to overcome DQ challenge.**

if' impact analysis using *fit-for-purpose data* [96]. From the perspective of DE for SDGs, the work done by [17], [97], [98], [99], [100], [101] has proved DE's capability to support the implementation and monitoring of SDGs. However, DE, as a *system of systems* already, also, like the SDGs, faces DQ issues [3], [14]. In the next section, we discuss overcoming the DQ challenge in DE for SDGs (particularly the issues surrounding DQ dimensions like *Consistency* and *Availability*) through IoT to complement DE for SDGs as reviewed in the literature.

V. Overcoming the Data Quality Challenge in Digital Earth for Sustainable Development Goals through Internet of Things

Although satellite data has been a major source of data for DE functioning, at times it lacks detail at fine-grained spatiotemporal resolution levels, as seen in SDG-11 Sustainable Cities and Communities (disaster management) [102], [103], SDG-13 Climate Change (fighting climate change) [104], [105], and SDG-14 Life Below Water (safeguarding life underwater) [106], [107], [108]. In this situation, IoT-enabled data can be important in covering the global need for *fit-for-purpose data*. Deployment of IoT systems has enabled efficient environmental monitoring, resulting in the generation of large amounts of in-situ monitoring data [109], [110], [111]. This IoT-enabled in-situ monitoring provides data at fine granular levels [112], [113], overcoming various DQ issues, particularly surrounding *Consistency*, *Availability*, *Completeness*, *Currency*, and *Trustworthiness*, highlighted in this study. In the context of DE since its inception, DQ has remained a significant issue, particularly the DQ dimensions like *Consistency*, *Availability*, and *Trustworthiness* [3], [95], [114], [115]. SDGs, especially those related to the Earth's surface, environment, and resources, exhibit significant scale and recurring transformations [16], [116]. By adopting a multi-dimensional approach, primarily considering global, regional, national, and local levels, highly *suitable* (or *fit-for-purpose*) data can be harnessed through a combination of satellite data and IoT data to support the realisation of the SDGs while creating a *system of systems* through an IoT-enabled DE, as depicted in Figure 3.

One example of the DQ challenge with satellite data can be seen when accessing environmental data, using for example, the Copernicus portal (*https://browser.dataspace.copernicus.eu/*) and finding certain values are missing. We accessed cloud cover data for the Republic of Ireland for a particular day using this portal, as can be seen on the top left in Figure 4. This depicts the presence of a high density of cloud that day (*blue color depicts being most dense as per Copernicus guideline*). We then accessed data on gases (Carbon Monoxide, Nitrogen Dioxide and Sulphur Dioxide) for the same day, and as can be seen on the top right, bottom left and bottom right in Figure 4, the data is missing for these gases for the areas under a high density of cloud cover. This scenario highlights the issue of the *Availability DQ dimension* for these gases, presumably because of the cloud cover. A similar scenario is discussed in [117] outlining that cloud cover increases the concentrations of nitrogen oxide at ground level, compounding the data gaps, as interpolation or estimation models to fill cloud cover gaps

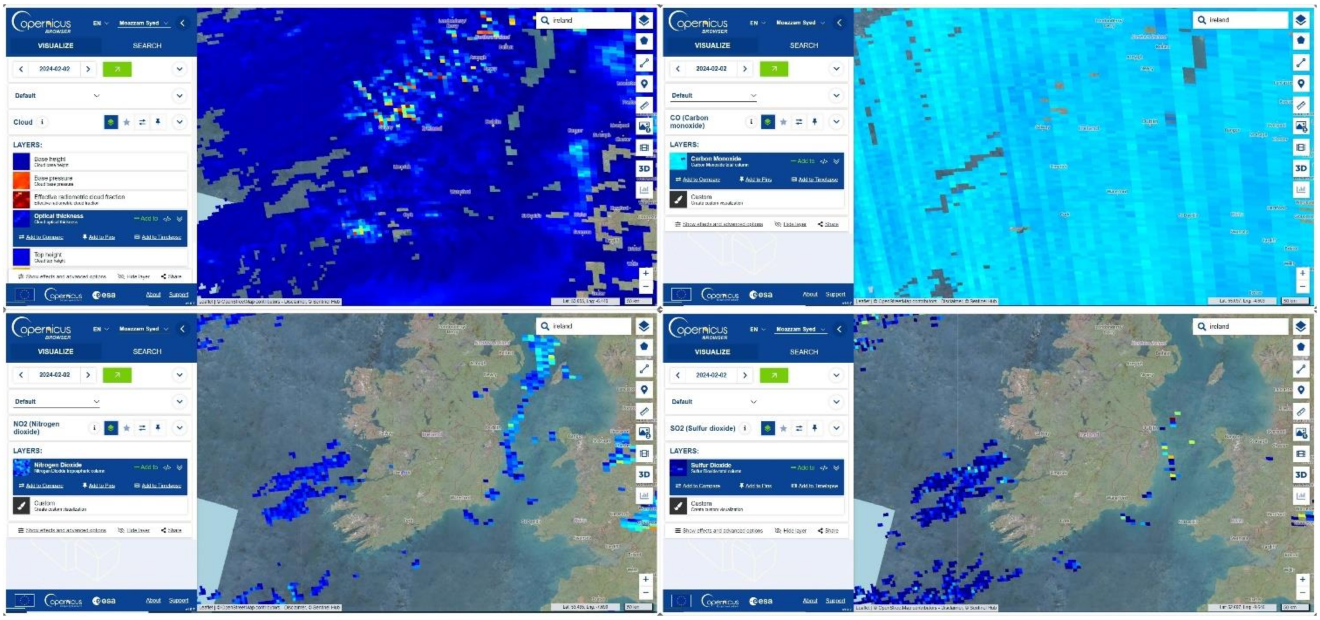

FIGURE 4. Sentinel-5P imagery of Republic of Ireland on 2.2.2024 showing data for Cloud Cover, Carbon Monoxide, Nitrogen Dioxide and Sulphur Dioxide. (Copernicus Sentinel Data 2024).

do not necessarily take into account the blanket effect of cloud cover.

This gives rise to the question of how to overcome the missing satellite data (*Availability DQ dimension*) as a result of conditions such as cloud cover. The combination of satellite and IoT data has already proved useful to overcome data inconsistencies in the former and enhance the coverage area as reported in studies by Phan et al. [118] and Barbedo [119]. Groundtruthing satellite data with IoT data can also be seen as one of the examples of how the combination of satellite and IoT data sources can enhance the overall DQ of data and address the DQ challenge in the broader perspective [120].

Although IoT has the potential to support DE implementation as shown in Figure 3 to overcome data gaps and cater to the DQ issues faced by DE, a substantial challenge arises when two *system of systems* (IoT and DE) combine to make a new *system of systems* (an IoT-enabled DE). IoT comes with its own DQ challenge, often lacking semantic interoperability and attaining information and/or knowledge exchange [121]. DQ dimensions like *Format*, *Ease of Understanding*, *Interpretability*, *Relevance*, *Granularity*, *Reputation*, and *Usability* as outlined in Table 2 need to be dealt with effectively to achieve data reusability and information utilisation as well as data sharing across domains and platforms [122], [123], [124]. Resultantly, this can help domain experts and eventually the decision-makers in attaining exchangeable knowledge between systems to support the sustainable development agenda. However, data reusability and information sharing can only be attained if system interoperability is achieved to the semantic level where knowledge is exchanged between systems rather than data [85]. Referring to the question raised in section two, we discuss in our next section whether the data available is *suitable* and *fit-for-purpose* to complement an IoT-enabled DE for SDGs transparently.

VI. Data Quality Challenge in an Internet of Things-Enabled Digital Earth for Sustainable Development Goals

Attaining semantic interoperability is important for a *system of systems* to produce and exchange information and/or knowledge rather than the data, especially when it comes to supporting dynamic goals like SDGs as we have discussed previously and as observed in the literature. Establishing *reproducible*, *replicable*, and *reliable* information and/or knowledge is a critical prerequisite among decision-makers and the public to put their *trust* in data and the decisions associated with it. It is important to note that they are interdependent on one another [125]. This *trust* in data is particularly important for the SDGs agenda [126]. *Reproducibility* is defined as "*obtaining results consistent with a prior study using the same materials, procedures, and conditions of analysis*", and *Replicability* is defined as "*obtaining consistent findings across studies that aim to answer the same question but with each study collecting and using its data*" [127], [128], [129], [130], whereas *Reliability* is defined as "*the extent to which measurements can be replicated*" [131].

This *reproducible*, *replicable*, and *reliable* information and knowledge could be harnessed to support decision-making surrounding SDGs through an IoT-enabled DE if the system interoperability is achieved at the semantic level [89], [132], [133] as observed in the health domain where diverse systems exchange knowledge rather than data [134], [135], [136]. However, the current state of data and data model interoperability in Earth Sciences remains limited to the syntactic level, which only enables the access and processing of datasets without considering their contextual attributes or

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standardised details of their content and contextual relevance [137]. This limitation to the syntactic level gives rise to the DQ challenge particularly surrounding the DQ dimensions like *Consistency*, *Format*, *Ease of Understanding*, *Interpretability*, *Relevance*, *Granularity*, *Reputation*, and *Usability* [138], [139], [140], [141] where data is not recorded in a unified way. Consequently, the lack of semantic interoperability hinders the reusability of data as well as knowledge sharing across domains for research, development, and decision-making purposes, particularly surrounding SDGs [142], [143].

Currently, information systems lack semantic interoperability as a result of which they cannot coherently trade information and/or knowledge with one another in most cases, and if the information and/or knowledge exchanges take place, they are often delayed [144]. System interoperability has the potential to address user expectations of accessing timely data [22]. Semantic interoperability within data and across information systems enables data handling from acquisition and quality assurance to data exchange, dissemination, and application usage [145]. Consistent standards for recording and representing data (DQ dimensions *Format*, *Interpretability*, *Ease of Understanding*, *Ease of Access*, *Granularity*, *Consistency*, *Accuracy*, and *Completeness*) are important for building user confidence in interoperable systems [146]. In general, standardisation is needed for the adoption of agreed-upon protocols and procedures between different observing platforms and their data management and product delivery systems [147], [148].

Without standardised (or consistent) metadata, it becomes difficult for different organisations or systems to exchange, understand, and use environmental data effectively [89], [133]. This also answers the question we raised in section two, and also answers the traceability concern in data used for developing EVs which we raised earlier. The amount of *trust* organisations or people may have in the data reduces when the data lacks *consistency*, *contextual richness*, and *quality*, particularly hindering the transparency of data as in whether the data processed is the same that was collected originally, or it has been changed during the processing stage. To give a better understanding of this DQ issue (or data inconsistency) at this point, we provide some scenarios from the literature to understand the state of data across domains representing data from three SDGs, in Earth Sciences, and the DQ issues that may arise.

A. *Scenario 1: Inadequate Rainfall Prediction and Satellite Data Limitations in Africa [149] – SDG11 Climate Change*

The work by Dinku in [149] highlights that the meteorological observation network in Africa faces significant inadequacies, characterised by a decline in station numbers and subpar DQ, compounded by an uneven distribution of stations with a bias toward urban areas and major roads, resulting in poor rural coverage. Moreover, this shortfall hampers the provision of climate services where they are most vital [150]. [35], [151]. It also identifies that satellite-based precipitation estimates are increasingly used, offering extensive spatial coverage, improved temporal and spatial resolution, and near-real-time availability to mitigate these issues. But these satellite products have their limitations, including accuracy problems (DQ dimension *Accuracy*) at high temporal resolutions, coarse spatial resolution (DQ dimensions *Precision*, *Usability*), short data records (DQ dimensions *Interpretability*, *Format*, *Reputation*, *Believability*, *Relevance*), and temporal inconsistencies (DQ dimension *Frequency*) [152]. Overcoming these DQ issues requires a rigorous validation process against ground observations for more consistent data, yet the availability (DQ dimension *Availability*) and quality (DQ dimensions *Accuracy*, *Precision*, *Completeness*, *Trustworthiness*, *Believability*) of rain-gauge data in Africa are a hindrance [153].

B. Scenario 2: Varying Data Usage Objectives Impacting Data Quality and Reusability of Marine Data [154] – SDG14 Life Below Water

Subsea mining, aquaculture, energy production, marine transport, and coastal tourism are significant marine sectors [155] with distinct needs for different types of in-water data sources and DQ levels. For instance, data related to the physical aspects of the ocean (like temperature and turbidity) and biogeochemical factors (such as pH and oxygen) are crucial for environmental and climate models [156]. It is also essential to have highly accurate temperature data of the ocean with minimal measurement uncertainties, around 0.002°C [157]. Conversely, in most aquaculture scenarios, a temperature sensor with an accuracy of ±0.5°C suffices [158], [159]. These varying requirements mean that data suitable for one purpose might not meet the quality standards of another (DQ dimensions *Consistency*, *Interpretability*, *Usability*, *Relevance*), leading to limited use of a particular in-situ marine data set, which was originally intended for multiple applications [160], [161]. In the marine field, data collection has primarily been guided by the needs of separate applications and usages of industry [154]. This means that data is often collected in isolation, without considering the potential usefulness for other applications (DQ dimensions *Format*, *Ease of Understanding*, *Interpretability*) [162]. Since collecting data in the marine environment can be quite expensive, it is crucial to make the most of in-situ marine data by using it for multiple purposes (DQ dimensions *Format*, *Interpretability*, *Usability*, *Accuracy*, *Completeness*) [163], [164] to share data and information across domains and platforms.

C. Scenario 3: Unavailability of Reporting Formats for Leaf-Level Gas Exchange Data [165] – SDG15 Life on Land

At present, most data repositories that house a variety of data tend to focus on providing general package-level details about the data, rather than offering specific information tailored to the type of data (DQ dimensions *Format*, *Interpretability*).

Thus, hindering the usefulness of, searching for, and discovering long-tail data types [166]. Examination of existing data repositories and databases by [165] related to plant traits has shown that, when it comes to data on leaf-level gas exchange, the available information is often incomplete and inconsistent (DQ dimensions *Completeness* and *Consistency*), lacking the necessary metadata for proper interpretation and reuse. There is a recognised need for data standards in various fields, particularly in ecophysiology [166], [167], and the importance of establishing standards for collecting and storing plant trait data has been highlighted in several recent studies [168], [169], [170]. Furthermore, gas exchange instruments do not adhere to a common output format (DQ dimension *Format*), including file structure, variable names, and units, and often use non-machine-readable column headers, which ultimately limits the usability and lifespan of the data [165].

D. Scenario 4: Lack of Standardisation Framework for Bio-logging Data [171] – SDG14 Life Below Water

Technologies like acoustic telemetry, light-based geolocation, and various data logging and transmission methods are generating data at unprecedented rates, opening up opportunities for synthetic studies [172], [173], [174], [175], [176], [177] that can address conservation issues stemming from global environmental changes [178], [179], [180] and extreme events [181], [182]. However, managing this data is quite challenging. Despite the emergence of numerous collaborative initiatives on regional and global scales aimed at consolidating existing biologging data [183], there is a lack of widely accepted data and metadata standards (DQ dimension *Format*) giving rise to data inconsistency (DQ dimension *Consistency*), hence most of the existing biologging data remains hidden and inaccessible [184]. The absence of universal and consistent standards for biologging datasets impedes progress in ecological research and places a significant burden on researchers due to technical and administrative obstacles when sharing and reusing data [185]. These problems span from immediate concerns regarding merging dissimilar datasets to the absence of an overarching framework that ensures (a) accurate use, (b) proper attribution and ownership, and (c) data preservation security [186].

VII. Discussion – Perspectives on Data Quality Solution, Data Reusability and Knowledge Sharing

Data plays a significant role across various scientific and societal domains in understanding complex connections between different aspects of global sustainability and improving our ability to access and analyse it is crucial [187], [188]. However, to integrate data from diverse sources effectively, we need to address the DQ challenge as identified in this study, particularly related to inconsistent levels of data detail, incompatible data formats, and data completeness. As seen in the scenarios discussed in the previous section, the lack of consistent data, agreed-upon standards for data, as well as metadata recording, limits data interoperability and reusability as well as knowledge sharing. All data levels generated through various sources or provided by various data providers need to be structured to ensure that data and metadata remain linked during data exchanges within or across domains [189], [190].

A. Building Trust in Data

One of the priorities for planetary intelligence for sustainability and/or sustainable development is '*building trust*'[191], [192], [193]. This '*building trust*' is what we pointed out in the question we raised in section two, and it is answered in the previous section. Environmental data, which is readily available needs to be *suitable*, *fit-for-purpose*, *consistent*, and *transparent* to be *trusted*. For this, the use of IoT data can significantly increase *consistency*, *completeness*, *timeliness*, and *transparency* in environmental data particularly to very micro levels in an IoT-enabled DE for SDGs as suggested in this study based on evidence present in the literature. Combining satellite and IoT data to address the DQ challenge needs further investigation to fully exploit the potential of the proposed *system of systems*.

The priority of *building trust* in information and knowledge is important for DE as well as DE for SDGs and addressing the DQ challenge can significantly enhance the *trust*. To overcome the DQ challenge it is important to achieve data *consistency* and enable data *reproducibility*, *replicability*, and *reusability* for knowledge sharing. These elements are also critical to knowledge sharing in the Earth Sciences domain, where standardised (or common) practices need to be adopted by the wider Earth Sciences community.

B. Standardisation as the Way Forward

Standardisation plays a critical role in adoption of community-wide agreed methods on efficient data management which furthers the notion of accessing and reusing data. The EU INSPIRE Directive is a successful example of how adoption of data standards can ensure harmonised, accessible, and interoperable geospatial data across any country and borders [194]. The EU INSPIRE Directive[1] is a regulatory framework aimed to support European environmental ambitions by making geographic information more consistent and readily available across sectors and borders. The International Standards Organisation (ISO) data standards such as ISO-19115[2] for metadata and Open Geospatial Consortium (OGC) data standards such as OGC Observations & Management (O&M)[3] correspond with the EU INSPIRE Directive by providing critical guidelines that the Directive builds upon. O&M provides conceptual models to encode observations and measurements from sensors and has been adopted by consortia like Copernicus[4].

While the process of standardisation through ISO might be slow due to their systematic procedures, other Standards

[1] https://knowledge-base.inspire.ec.europa.eu/index_en
[2] https://www.iso.org/standard/80275.html
[3] https://www.ogc.org/standard/om/
[4] https://www.copernicus.eu/en

Developing Organisations like Open Geospatial Consortium (OGC) have proven to be more agile standards' developers [195]. A number of OGC data standards have come to prominence in recent years and proven their efficiency. Web Processing Service (WPS), WaterML, SensorThings API, and Sensor Observation Service (SOS) by OGC are some of the examples of successful standards that have enabled accessing and reuse of data within the Earth Sciences domain [196], [197], [198]. WPS provides an interface to publish and search collections of metadata for data over internet[5]. WaterML allows the representation of water observation data with the intent of promoting the exchange of related datasets across information systems[6]. The SensorThings API provides a unified geospatial-enabled JSON-based way to interconnect and task IoT devices, data and applications over internet[7].

The progression of standardisation through standards like ISO-19107 (Spatial Schema)[8], ISO-19109 (Rules for Application Schema)[9], ISO-19123 (Coverage Geometry and Functions)[10], OGC Simple Feature Access (OGC-SFA)[11], ISO-19115[12], ISO-19110[13], OGC O&M[14], Simple Knowledge Organisation System (SKOS)[15], Network Common Data Form (NetCDF)[16], Hierarchical Data Format (HDF)[17], and Geography Markup Language (GML)[18] has enabled domain experts to define information models, terminologies and datatypes in a more accessible and standardised way in the Earth sciences domain. Such standardisation efforts have led a number of national and international organisations to adopt unified ways for good data management. Despite their potential, the adoption of these standards is still not mature within the Earth Sciences domain.

In the broader perspective, it is important to acknowledge that no dataset is any less important than other datasets as they contribute together to the pool of knowledge generation [199]. In the recent times, we have seen some well-curated specific purpose data repositories (such as GenBank[19], Worldwide Protein Data Bank[20]) getting popularity. However, these do not capture every dataset or datatype because of their 'specific purpose' nature. In response to these repositories, a number of general-purpose repositories have emerged, such as Dataverse[21], Zenodo[22], DataHub[23]. Although these repositories accept a wide range of datasets, these datasets are different in their structural nature. Having no standardised dataset structure compounds to the problem of accessing, integrating, or reusing the data [200]. For instance, a machine may be able to determine the datatype of a certain dataset, but not capable of parsing it because of the format being unknown. Or it might be capable of processing data contained inside, but not capable of determining details concerning the retrieval and/or use of that data. Creating dedicated parsers in a number of languages for a range of datatypes might provide a short-term solution but it is not a sustainable solution and furthers the problem. The way forward to good data management remains the efficient adoption of community-wide agreed standards on information models, coding systems, and datatypes.

C. Essential Variables as Agents for Data Reusability and Knowledge Sharing

As highlighted earlier in the study, the development and usage of EVs, is a promising mechanism to utilise the data (reusability) and knowledge sharing for enhanced decision-making surrounding sustainable development. The holistic approach of EVs to capture the diverse aspects of Earth Systems through the data complements, in particular, the *Availability* DQ dimension, which is highly important as nations across the globe continue to struggle with SDGs and the UN 2030 Agenda. Despite their potential for knowledge sharing and data reusability, EVs are not without their challenges and weaknesses either. Earth systems are interconnected and complex, therefore defining a set of EVs that capture their complexity entirely while remaining practicable for monitoring can be challenging [201], [202].

On the other hand, ensuring the quality and consistency of satellite data across different observation platforms, which is reused and fed into the EVs for knowledge sharing, is a continuing challenge [203]. Variability in measurement techniques, calibration, and validation procedures can lead to inconsistencies in the data used in EVs [204], hence adding to the DQ challenge and creating doubt in the workflow and/or decision-making affiliated with the EVs. The addition of IoT data enhances DQ and thus increases the level of trust in the data that feeds into the EVs. This leads to an increased level of trust in EVs knowledge sharing during the decision-making process. This aspect remains a promising future research direction in the Earth Sciences domain which needs to be further investigated to exploit the full usage of EVs.

D. Two-Level Information Modelling as a Pathway towards Data Reusability and Knowledge Sharing

Advanced-level semantic interoperability approaches [89], [205] used in other domains such as the use of two-level information modelling in the health domain, present a potential solution to overcome the DQ challenge by enhancing data reusability (*Availability DQ dimension*) as

[5] https://www.ogc.org/standard/wps/
[6] https://www.ogc.org/standard/waterml/
[7] https://www.ogc.org/standard/sensorthings/
[8] https://www.iso.org/standard/66175.html
[9] https://www.iso.org/standard/59193.html
[10] https://www.iso.org/standard/70743.html
[11] https://www.ogc.org/standard/sfa/
[12] https://www.iso.org/standard/80275.html
[13] https://www.iso.org/standard/57303.html
[14] https://www.ogc.org/standard/om/
[15] https://w3.org/2004/02/skos/
[16] https://www.unidata.ucar.edu/software/netcdf/
[17] https://www.hdfgroup.org/
[18] https://www.ogc.org/standard/gml/
[19] https://www.ncbi.nlm.nih.gov/genbank/
[20] https://www.wwpdb.org/
[21] https://dataverse.harvard.edu/
[22] https://zenodo.org/
[23] https://datahubproject.io/

well as knowledge sharing in the Earth Sciences domain [206]. It is often logistically and technically difficult for data producers and users with large information models for domains to agree on a common data model which makes automated processing and decision-support using observational data very difficult to achieve [207]. The application of two-level information modelling in health informatics by Thomas Beale [206] addresses this and demonstrates the significance of considering structural attributes when accessing and processing datasets [132], [206], [208] which we have observed are very important and apply to all datasets independent of their domain affiliation.

Beale's work emphasises the generation of data with secondary applications in mind, ensuring future utility (reusability) and enabling information systems to disseminate knowledge rather than raw data [209], [210]. The concept of '*archetypes*' introduced by Beale promotes smooth data exchange (interoperability), especially when data is gathered by and exchanged across diverse systems or applications, enhancing semantic interoperability [211], [212], [213], [214], [215]. These *archetypes* are used to describe knowledge while *ontology* is used to describe information in a dynamic environment that exhibits constant change in data. Expanding further on Beale's foundational work, Stacey and Berry [89], [133] successfully extended two-level information modelling beyond health informatics to geospatial observational scenarios, fostering semantic interoperability and data reusability within Spatial Data Infrastructures (SDIs). Lezcano et. al [205] observed that utilising '*emergency archetypes*' offers benefits such as seamless integration of semantic data and adaptability to incorporate new types of messages all while maintaining the capability for smooth communication between heterogenous Emergency Response Management systems. Diviacco and Leadbetter [216] emphasise that despite the difficulties in collaborative research enabling knowledge generation in the domain of sustainable development, particularly in Earth Sciences, there are opportunities through the exploitation of a careful balance of formalised knowledge and non-formalised knowledge representation using two-level information modelling, particularly vocabularies like archetypes or ontologies. Referring to the research gap identified in the previous subsection, diverse IoT-based EV data can be merged using two-level information modelling to enhance overall DQ, as it supports a rigorous form of data source diversity that can be integrated.

We conclude the discussion with the observation of Wilkinson et al. [199] that the nuance of good data management is not a goal itself, but rather an important aspect that leads to knowledge generation, discovery, integration and reuse. Other than collecting the data and its archiving, good data management is the idea of long-term vision (or care) of data with the ultimate goal of data discovery and reuse either in its own fragments or in combination with new data. This approach addresses one of the big challenges of identifying, accessing, integrating and analysis of required data for any task at hand. Our study explored various viewpoints on DQ issues based on literature, particularly at the reasons that give birth to DQ issues – all of them (more or less) pointed towards the lack of standardisation and its adoption across the domain. Domain-based standardisation and its adoption can be an immediate as well as effective way to deal with DQ issues arising within the Earth Sciences domain. It may also open an effective way of using IoT-based data in DE, which in return could be used for decision-making surrounding SDGs. Data serves as a cornerstone to decision-making when it becomes information and contributes to the knowledge pool our science community needs. Eventually, this may also serve as one of the important steps towards achieving the *Data-Information-Knowledge-Wisdom* pathway which is central to addressing the significant environmental issues our planet faces today with the future of our generations and the health of the planet at stake.

VIII. Conclusion

Today, just over halfway through the 2030 Agenda for a Sustainable World, the global community faces more critical issues than ever. Achieving a sustainable world, particularly the SDGs agenda, requires the utilisation of diverse data from fields like climate, water, ecology, agriculture, social sciences, and economics for enhanced decision-making and knowledge sharing. DE is essential for processing these broad, dynamic, and complex datasets, offering a real-time visual representation of knowledge and processes occurring within the Earth system. However, both DE and SDGs in general and DE for SDGs in particular face a dearth of DQ. This study identified the DQ challenge as one of the major obstacles in achieving efficient and effective functioning of DE to complement sustainable development as well as SDG implementation monitoring. It also identified the DQ challenge as a major hindrance in knowledge-sharing within the Earth Sciences domain.

To overcome the critical DQ issues, particularly *Availability*, *Completeness* and *Consistency* DQ dimensions, this study identified IoT as a provider of viable data sources that can complement satellite data, enhancing the granularity, consistency, and temporal resolution of data, hence giving birth to the idea of IoT-enabled DE for SDG, and helping to overcome the DQ challenge. However, IoT data also comes with its own DQ challenge as observed in various scenarios outlined in section VI. These challenges include lack (or adoption) of agreed-upon standards for data collection, processing, storing, and/or validation, continuing to hinder the DQ within the Earth Sciences domain. Data is often inconsistent – can be collected and distributed without sufficient metadata or context contributing to the DQ challenge and hindering researchers and scientists collaborating across various domains due to the lack of trust and transparency in data collection, processing, and/or validation. This results in barriers to data reusability, applicability, knowledge-sharing, and data reproducibility. It also leads to the inefficient duplication of data collection efforts which costs both time as well as resources.

Finally, the study also identified standardisation as the way forward including some potential candidates as solutions for the enabling data reusability and knowledge sharing i.e., EVs and Two-level Information Modelling in the Earth Sciences domain, which remain open as promising future research directions. To unlock the full potential of an IoT-enabled DE for SDGs or the *system of systems* in general, ensuring DQ is critical and central to data reusability, information, and knowledge-sharing. Putting trust in the data is crucial, given the need for combined efforts from diverse fields with unique languages and data formats in addressing ever-changing global needs.

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DATA AVAILABILITY STATEMENT

No work on a new or existing data has been carried out in this study.

CONTRIBUTION OF AUTHORS

M.S.B.S prepared and furnished the idea for this study, conducted literature research, drafted, and revised the manuscript. P.S., P.K. and D.B. contributed to reviewing the manuscript, ensuring its accuracy, coherence, and relevance.

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