Journal of Science and Engineering Applications Vol. ٨, No. ١, pp. xx–xx, April 2026

Journal of Science and Engineering Applications

Contents are available at https://jsea.iujournals.com

The Role of the Semantic Web in Healthcare and Sustainability

Ahmed Mounaf Mahdi[1], Ahmed S. Al-akayshee[2]

[1]*Jabir ibn Hayyan University for Medical and Pharmaceutical Sciences, Najaf, Iraq*
[2]*Department of Medical Instrumentation Techniques Engineering, College of Technical Engineering, The Islamic University Najaf, Iraq*

ARTICLE INFORMATION

Received date: ٢٠٢٦-٠١-١٥
Revised date: ٢٠٢٦-٠٣-٧
Accepted date: ٢٠٢٦-٠٤-٢٠

Keywords

Semantic Web
Healthcare Informatics
Sustainability
Linked Data
Ontologies

ABSTRACT

The Semantic Web (SW) is starting to change how we understand complex data across different disciplines. This review explores the importance of SW in systems that combining medicine and sustainability. These two fields need structured data and governed data systems. We examine the utilization of SW technologies in clinical decision support systems (CDSS), electronic health records (EHRs), and environmental monitoring systems. In healthcare especially, these technologies enhance the accuracy of diagnosis and help in integrating heterogeneous health systems. In addition to developing the personalized care systems. In sustainability, these technologies help in the assessment of life cycle and in preparing environmental policies. In addition to ecosystem-wide data synthesis through vocabularies like ENVO and SWEET. At the intersection of health and environment, SW supports interdisciplinary models like Planetary Health and One Health through linked data approaches that is used to understand the climate-sensitive diseases and sustainable public health. The current challenges are also discussed in this review which consist interoperability, privacy, reasoning scalability, and highlight. Future directions, including AI integration, federated knowledge graphs, and regulatory frameworks are highlighted as well.

1. Introduction

The complexity of health and environmental challenges leads to the need of intelligent and semantically rich systems. The Semantic Web (SW), which is an evolution of the current web architecture, provides a solution that converts data into machine-readable, machine-understandable knowledge by utilizing formal semantics and linked data structures [1]. The use of SW in medicine has shown promise in enhancing diagnostic precision, knowledge discovery, and electronic health record (EHR) integration for personalized and precision medicine [2, 3]. Moreover, its use in sustainability science makes environmental monitoring and policy modelling more intelligent [1]. The intersection of these fields -medical with sustainable data- remains an emerging research frontier.

In 1994, Tim Berners-Lee recognized the importance of incorporating semantics into the web to publish

* Corresponding authors: Department Name, University Name, Bangladesh
E-mail addresses: email@xxxxx.com (Author Name)

structured data and extend its functionality, and the SW was born. The SW introduces a knowledge infrastructure where data can be queried and reasoned over using shared vocabularies and graph-based models. Core technologies include: RDF (Resource Description Framework) which is a W3C recommendation for defining resources and distinguishing relationships with other resources using a graph-based data model (subject – predicate – object), OWL (Web Ontology Language) for defining rich ontological hierarchies, and SPARQL for querying RDF datasets [4].

Large amounts of RDF data were published in publicly accessible datasets linked together to create the so-called linked open data (LOD) cloud. The knowledge included in LOD is important in sectors such as healthcare and environmental policy. In biomedicine, Semantic Web approaches support clinical interoperability and decision-making system through ontologies such as; the systematized nomenclature of medicine clinical terms (SNOMED CT) [5], Logical Observation Identifiers Names and Codes (LOINC) [6], Fast Healthcare Interoperability Resources (FHIR) [7, 8], and Gene Ontology [9]. In sustainability, vocabularies like Environment Ontology (ENVO) and the Semantic Web for Earth and Environmental Terminology (SWEET) facilitate cross-disciplinary data integration in climate modeling and land use change detection domains [10]. Table 1 below shows the common ontologies with their domain, use case, and the website for each ontology.

Table 1. Ontologies for Medicine and Sustainability

Ontology Name	Domain	Use Case	Website
SNOMED CT	Medicine	Clinical terminology standardization	https://www.snomed.org/
FHIR	Medicine	Interoperability for healthcare data exchange	https://www.hl7.org/ fhir/overview.html
Gene Ontology	Medicine	Functional annotation of genes and proteins	https://geneontology.org/
LOINC	Medicine	Standardizing laboratory test codes	https://loinc.org/
ICD-10	Medicine	Coding diseases and health conditions	https://github.com/icdo/ICDO
ENVO	Sustainability	Environmental data classification	https://github.com/Env ironmentOntology/envo
SWEET	Sustainability	Earth and climate science semantic integration	https://earthportal.eu/ ontologies/SWEET

The combination of health and sustainability is very important for example, using air quality data to contextualize chronic disease patterns, this can be modelled semantically to improve precision public health and help policy makers to create policies and increase the awareness by guiding the medical education [11].

This review investigates the effect of SW technologies on supporting precision healthcare, and climate-resilient public health as well as sustainable policy innovation. It highlights case studies, ontology systems, AI-semantic integration, and the role of semantic reasoning in linking human health with his environment.

2. Semantic Web in Medicine rmatting your paper

SW technologies are utilized in many fields including medical field through interoperability, and knowledge discovery in healthcare ecosystems. Many applications have benefited from SW technologies for clinical decision support and for integration of electronic health records (EHR). In addition to drug diagnosis that uses ontology to deal with diseases.

The use of ontologies such as SNOMED CT, LOINC, and the Gene Ontology for representing clinical data in order to make reasoning engine generates alerts, recommendations, and insights in real-time. Integration of SW with AI is widely used to enhance the decision-making capacity of CDSS. For example, approaches that combine rule-based reasoning with Support Vector Machines and Bayesian networks can interpret 3D biomedical data precisely and support complex diagnoses [2].

Matulewicz, et al. [12] have evaluated the impact of EHR-integrated CDSS in promoting guideline-concordant evaluations. The approach aimed at improving diagnosis for high-risk microscopic hematuria through Semantic Web-informed CDSS. The result showed feasibility but modest clinical uptake and it needs for enhancing algorithm design and make it more user friendly. Furthermore, semantic systems have been instrumental in standardizing transfusion practices through evidence-based CDS tools. Czako and Prochaska [13] found that sometimes the systems cannot align to the clinical guidelines or adapt to any evidence. Therefore, dynamic updates in necessary in addition to context-aware customization.

There is growing interest in integrating natural language processing (NLP) with SW for question answering, document summarization, and personalized education in medicine especially with the rise of large language models (LLMs) [14]. These systems highlighted the importance of SW technologies as the backbone for AI-driven healthcare.

3. Semantic Web in Sustainability

SW technologies are important in developing environmental sustainability and climate resilience through enhanced data interoperability and real-time monitoring. In addition, it helps policy maker to enhance their policies and depend on evidences in policymaking. SW help unifing diverse data sources across sectors such as climate science, biodiversity conservation, and sustainable urban planning.

Environmental monitoring is an essential use case, where SW combined with AI techniques for image processing to help in land-use change detection specifically, in sensitive ecosystems. Gong [1] utilized a SW with superpixel segmentation and machine learning classifiers (SVM, RF, NB) to detect land degradation with high accuracy, therefore, supporting sustainable solution for land management and policy design. The role of ontologies such as ENVO and SWEET is crucial. These vocabularies standardize environmental concepts and facilitate cross- dataset queries, which are essential for life cycle assessments and eco-regional planning.

Ridley, et al. [15] proposed web-based evidence entry form for extraction of cause effect relationships. The approach utilizes terminologies and structured data models for publications. This tool support consistent documentation and meta-analysis of cause-effect relationships in ecological literature.

At the policy level, semantic-based systems support the energy transition and sustainable finance solutions. For example, semantic analyses highlighted the need for climate policies that not only interested in emission caps but also included renewable energy innovation and large-scale deployment such as installation of solar systems [16]. Similarly, sustainable banking services benefit from semantic models that map financial services with environmental criteria to ensure that the service is supporting environment [17].

All of these examples demonstrate how the SW serves as an activator of transdisciplinary data fusion. Using SW bridges knowledge gaps between environmental science, economic systems, and social policy to get sustainable outcomes.

4. Interdisciplinary Integration

The intersection of medicine and environmental sustainability represents a critical factor in global health. The SW, with its ability for semantic reasoning and ontology alignment, serves as a unifying model to link clinical, environmental, and social data under shared paradigms such as; Planetary Health and One Health.

The One Health framework recognizes the connection between human, animal, and ecosystem health. Muntasir, et al. [18] integrated traditional medicinal practices with modern clinical interventions in a rabies control program in Indonesia by converting traditional data into structured formats, such integration enhances both cultural and environmental sustainability. The approach identified local practices, analyzed their integration with modern medical interventions, and educated the community about rabies prevention. [18].

In the Planetary Health paradigm, which focus on identifying common features of environmentally and socially engaged community programs, specifically those addressing the intersecting challenges of planetary and human health [19]. These programs need to be analyzed using a structured model, identified “connection to nature,” “collaboration,” and “preventive measures”. Those are critical elements each can be benefit from a semantic model that can integrate diverse data sources for monitoring and evaluation. The integration of these two approaches highlighted the need of Linked Open Data and cross-domain ontologies such as the integrating of SNOMED with ENVO to enhance decision support systems. Such systems that track disease vectors influenced by climate can also guide sustainable healthcare infrastructure and preventive strategies.

5. Challenges and Limitations

SW technologies face several technical issues and ethical limitations that may reduce their utilization in some domain, especially in medicine and sustainability because such domains have complex data structures that lead to data heterogeneity, semantic differences, lack of standardization and privacy.

5.1 Interoperability Complexities

When dealing with heterogeneous datasets and cross-domain ontology alignment, a challenge will appear called semantic interoperability. To tackle this challenge many approached proposed in previous works. For instance, El Ghosh, et al. [20] developed a layered modular hyper-ontology in cancer data model. This ontology bridges the disparate imaging and clinical knowledge of the various repositories in EUCAIM and supports their integration. They highlighted in their approach the feasibility and complexity of semantic integration and determine as a future work the need of revising the ontology content based on the feedback from the experts for enrichment purposes and for additional new use cases and new cancer types. Hamdan, et al. [23] also tackle this challenge by proposing an approach that utilizes an ontology to bridge such gaps in cloud environments.

5.2 Privacy and Federated Learning

Data privacy is a significant challenge in medical domains for sensitive patient data such as Personally Identifiable Information and protected health information. Many approaches were proposed to tackle this issue; one of them is data decentralization. Federated SW architectures offer an effective solution by keeping data decentralized while enabling local training and share updates only. In financial risk control, Gupta et al. [21] utilized federated learning principles for privacy-preserving data sharing and approve its effectiveness when it is implemented in healthcare or environmental surveillance domains.

5.3 Reasoning Performance and Scalability

Semantic reasoning engines often suffer from scalability issues and computational issues. Knowledge graph can be increase in size dramatically and this led to increasing the query response times and inference reliability can also be degraded. Gupta, et al. [22] investigated a federated semantic querying approach and highlighted the need for optimized algorithms and modular architectures to maintain performance standards in distributed settings.

6. Future Directions

6.1 AI and Semantic Convergence

The convergence of AI and SW technologies will support clinical decision-making and can be utilized in personalized medicine, and sustainable development tracking. SW with deep learning and natural language processing, are expected to improve the processing of unstructured data and enhance medical image interpretation [2].

6.2 Federated Knowledge Graphs

These decentralized knowledge graphs enable secure, cross-institutional collaboration without transferring raw data and the data will be processed locally [21]. This is a good area for more research and can solve many issues.

6.3 Legal and Ethical Frameworks

The widespread of semantic-AI tools may lead to legal and ethical regulation violation. Issues like algorithmic bias, explainability, and equitable access need some policies. Al-Adwan and Qutieshat [24] emphasized the urgency of aligning Semantic Web-driven AI in medicine with international human rights and Sustainable Development Goals (SDGs) particularly those concerning good health and strong institutions[24]

7. Conclusion

This review shows that the SW technologies have vital role in medical field and sustainability by providing a framework for data interoperability, decision support, and recommending policies. In medical field, SW enhances medical decision making and diagnostics through the structured knowledge, In sustainability, it helps in environmental monitoring, climate policy design, and integrating data from different sectors through ontologies such as ENVO and SWEET. Combining medicine and sustainability helps to tackle complex challenges such as climate-sensitive diseases, community health and sustainable health delivery. Emerging trends such as AI-enhanced semantic reasoning, federated knowledge graphs, and policy-aware ontological system achieved excellent result in different domains. However, they are struggled by challenges related to semantic interoperability, privacy especially in medical field, and scalability. Addressing these problems requires legal framework, ethical standards, and interdisciplinary cooperation.

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