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Review

Sensor Applications in Agrifood Systems: Current Trends and Opportunities for Water Stewardship

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Abstract: Growing global food demand and security concerns dictate the need for state-of-the-art food production technologies to increase farming efficiency. Concurrently, freshwater overexploitation in agriculture, especially in arid and water-scarce areas, emphasises the vital role of appropriate water-saving irrigations techniques to ensure natural resources sustainability in food supply networks. In line with the development of automated systems, the use of sensors for water monitoring, indicatively in the cases of smart farming or precision agriculture, could further promote the preservation of freshwater resources. To this end, this research first provides a review of sensor applications for improving sustainability in agrifood systems. We then focus on digital technologies applied for monitoring and assessing freshwater utilisation in the food commodities sector based on academic literature and real-world business evidence. A contextual map is developed for capturing the main technical, environmental and economic factors affecting the selection of sensors for water monitoring and stewardship during agricultural production. This first-effort framework, in terms of sensor-based freshwater monitoring, aims at supporting the agrifood system's decision makers to identify the optimal sensor applications for improving sustainability and water efficiency in agricultural operations.

Keywords: sensor application; agrifood system; food supply network; freshwater monitoring; water stewardship

1. Introduction

Sustainability and resources stewardship in the agrifood sector have emerged as critical research topics in management science, considering the increasing global population and associated elevated nutritional needs [1], along with the intensifying anthropogenic activity in the international business landscape that raises societal and organisational competition over the scarce natural resources [2]. In particular, during the last 50 years, a three-fold increase in global dietary needs has been observed, while resources' appropriation exceeds by 30% nature's capability to regenerate [3]. Agriculture impacts heavily freshwater resources, as the sector consumes and pollutes nearly 70% of the global freshwater reserves [4]. Furthermore, approximately one third of all food produced worldwide is lost or wasted [5] across end-to-end food supply network operations [6]. To this end, the resulting need to replenish discarded food supplies intensifies freshwater appropriation both directly and indirectly [7].

Academic literature is being proliferated by studies identifying information and data elements necessary for conducting end-to-end food supply network modelling and analyses [8]; stakeholders

can then make informed decisions regarding natural resources' stewardship for promoting sustainability [9]. However, a lack of emphasis on the management of freshwater resources from a holistic supply chain perspective is evident in the literature [10]. In addition, to the best of our knowledge, only a limited number of studies has a pragmatic view over the technical ability to monitor the freshwater needs of crops and acquire data for guiding real-time precision farming and irrigation operations. In particular, efficiency in irrigation operations is deemed critical, due both to the variability of weather and climate conditions and to the farmers' limited capacity in accessing understandable agrometeorological information [11]. Increased awareness and real-time visibility of agro-field water needs could thus assist farmers in obtaining the benefits of freshwater resource management interventions (e.g., water-efficient irrigation, wastewater recycling and reuse, prudent use of fertilisers/pesticides [10]) and thus planning to increase productivity and mitigate regional water scarcity. In addition, recent evidence argues that ensuring freshwater sustainability could support the financial performance of agrifood supply networks in environmentally aware markets [12].

In this regard, the processes of digitalisation and traceability in food supply networks via sensor-driven operations could assist in promoting eco-sustainability [13]. Furthermore, due to the biological nature of food commodities, near-real-time traceability and tracing of distribution and storage conditions, food degradation effects and quality attributes, via sensory applications, could further foster consumers' trust [14].

In fact, sensors are deemed to be appropriate applications for monitoring occurrences of unexpected events and conditions that could affect the perishability of food product flows across supply networks, hence timely informing about actions for mitigating any associated risks. Typical data and information captured through sensors about warehouses, vehicles and containers used in food supply chains operations include [15]: (i) environmental conditions (i.e., temperature, humidity, concentration of CO_2); (ii) states of motion (i.e., irregular vibrations, unanticipated falls, inordinate tilt, illegal opening) and (iii) geographical location. Notably, temperature mismanagement during transportation may result in food quality decay and product losses of about 35% [16], while transport vibrations and shocks could severely compromise integrity and quality in particular of food products like fruits and vegetables [17].

Regarding water management in agricultural systems, the use of sensors to determine the water needs of crops compared to classical sampling-based techniques is recommended, as their application: (i) saves time; (ii) is not laborious and (iii) is feasible for large-scale farming [18]. These sensors can either be deployed at field/soil for informing intelligent irrigation systems [19] or be mounted on automated guided vehicles that perform farming operations to recognise the specific freshwater requirements of individual plants [20].

Overall, this research effort contributes towards providing a first 'mapping' of the existent sensors utilised for efficient freshwater monitoring or related operations to support decision makers in identifying the optimal automation-related solutions for promoting sustainable water management during agricultural processes. The remainder of the paper is structured as follows. In Section 2, a review of sensor applications across food supply chains is presented. In Section 3, emphasis is placed on commercial sensor applications for enhancing water stewardship in agrifood systems, through summarising the main types of sensors and related information. Finally, in Section 4, we conclude with the major insights and recommendations for future research.

2. Sensor-Focused Decision Making in Food Supply Networks

As empirical research argues that the perception of farmers about precipitation and temperature variability could affect the related adaptation strategies implemented [21], the use of sensors for real-time monitoring in agriculture emerges as an essential precondition for effective decision making. In addition, the perishable nature of food products, along with the variability of preservation, packaging and transportation conditions, impacts the products' remaining shelf life [22], further highlighting the catalytic role of sensor applications for the monitoring of food attributes and

environmental conditions. To that end, sensors can be used not only to enable visibility during agricultural production, but also to provide end-to-end traceability in food supply chains, particularly in the case of cold chains [23]. The retrieved data and information could inform efficient and responsive supply chain management interventions to mitigate food safety risks, improve inventory management, reduce waste and losses, as well as allow for dynamic pricing systems [24]. Recently, due to the improvement, accuracy, technical feasibility and economic viability of sensors, the use of wireless sensor networks in the agricultural sector is becoming the norm [25]. Indicatively, the use of wireless multi-sensor networks is utilised in the case of honey peach export chains to prevent unexpected food quality losses and to ensure transparency [26]. Ruiz-Garcia et al. [27] provided a review of sensor technologies applicable to the agriculture and food industry. Notwithstanding the enabling role of sensors towards sustainable food networks, their adoption and implementation by end-to-end food supply chains requires a robust decision-making process; Óskarsdóttir and Oddsson [23] provide a detailed decision-support framework for guiding stakeholders in cold food chains to identify appropriate traceability technology.

Sensor applications can foster proactive decision making in agrifood supply chains. Contò et al. [28] discussed the need for agricultural innovation and technology transfer from research organizations to multi-tier agro-system stakeholders, focusing on the Apulia region, Italy. The authors supported the traceability and certification of agrifood products, enabled by sensor-based RFID technology for ensuring efficient logistics operations and offering high quality, environmentally friendly and cost-effective agro-product flows. Li and Wang [29] proposed a dynamic pricing model, based on fresh vegetable predicted shelf life enabled by sensor-captured data, in a chilled food retail network in the UK. The provided analytical and simulation results encourage food companies to adopt data gathering and analysis related innovations to foster their competitiveness. Furthermore, Tamplin [30] discussed the need of integrating sensors and predictive models for monitoring alterations in food quality attributes across end-to-end food supply networks to mitigate the risk of food-borne illnesses and commodities' spoilage. The author described cases from the seafood and meat supply networks highlighting the 'Pathways to Market' project that facilitates digital information to increase the sales and value of Tasmanian food products. Wang et al. [26] deployed a real-time system for monitoring transport and storage conditions in perishable food supply chains via applying the ZigBee-standard wireless sensor network. The results highlight the feasibility of such systems in terms of both performance (e.g., high success data transmission rate of 99%) and viability (e.g., sufficient life time in terms of power consumption). Finally, Moharana and Dutta [31] examined alternative vegetation water indices to investigate the water stress variability in paddy rice agriculture in India during the pre-monsoon and monsoon seasons. Predictive models of leaf relative water content use data and imagery captured through both portable spectroradiometer and the Hyperion sensor on board the Earth Observing-1 satellite, respectively. Table 1 summarises the key decisions related to the application of sensor in food supply networks, as identified in peer-reviewed scientific articles, along with the targeted aims.

Table 1. Sensor-related decisions in food supply networks.

Reference	Sensor-Related Decisions	Supply Network Aim
Contò et al. [28]	• Create networks stressing multi-level stakeholders behaviours. • Facilitate the transfer of knowledge from research and agricultural innovation to agricultural sector. • Structure the portfolio of technologies and technology scouting activities. • Analyse the innovation needs. • Establish patterns of technology transfer.	• Quality • Food safety
Li and Wang [29]	• Decide on the information to be monitored (e.g., product identity, product batch/package identity, location, period of time at each location, temperature). • Develop dynamic food pricing model related to remaining shelf-life and based on demand response. • Allow real-time data gathering and analytics. • Articulate demand scenarios based on food pricing and shelf life.	• Dynamic pricing • Quality • Shelf life

Table 1. *Cont.*

Reference	Sensor-Related Decisions	Supply Network Aim
Tamplin [30]	• Adopt predictive microbiology models for describing changes in food quality as a function of environmental conditions.	• Quality • Food safety
Wang et al. [26]	• Decide on the architecture of the wireless sensor network, if applied. • Decide on the topology of a wireless sensor network, if applied. • Decide on the hardware and software implementation of the wireless sensor network, if applied.	• Quality • Shelf life
Moharana and Dutta [31]	• Decide on the wavelength range that potential optical sensors need to detect. • Decide on the indices that need to be calculated for describing agricultural water status. • Decide on the algorithms and models to calculate indices.	• Water content • Water stress

3. Sensor Applications for Water Stewardship in Agrifood Systems

Focusing on freshwater resources, spatial and temporal climatic changes, as well as uncertainties in weather conditions, can affect freshwater allocation [32]. Thus, the use of sensors during agricultural production can efficiently monitor soil moisture and water content, allowing for proactive decisions regarding irrigation and fertilisation operations [25]. Wireless sensor networks are the norm in agricultural production systems to monitor field conditions, water utilisation and climate variability, aiming to enable decision support systems regarding the scheduling of irrigation operations and the determination of individual plants' water requirements [33].

Indicatively, Sánchez-Molina et al. [34] studied alternative virtual sensors for designing irrigation controllers for tomatoes in coconut coir substrate in Almería, Spain, that elaborate data over the amount of water in three crop levels, namely: substrate, root and aerial part (including leaves, stems and fruit). Moharana and Dutta [31] used optical sensors for the evaluation of indices related to the leaf relative water content and growth of rice in India. Incrocci et al. [35] demonstrated the use of dielectric sensors and probes for controlling irrigation and fertigation of container ornamental nursery stocks in Pistoia, Italy, primarily irrigated via urban and peri-urban wastewater. The study results demonstrated freshwater savings of more than 50%, depending on the ornamental species. In addition, Fourati et al. [36] developed a web-based decision support system, enabled by a wireless sensor network, for monitoring evapotranspiration, rain water levels and soil moisture to support efficient irrigation scheduling for olive fields in Tunisia. Nolz [37] supported the use of a wireless network combining different sensor types to enable integrated water management in agriculture through real-time data monitoring. The author stressed the importance of calibrating weighing lysimeters and soil water sensors to directly quantify evapotranspiration, precipitation and soil water content for the accurate assessment of soil water balance.

Regarding the extended food supply networks, Wang et al. [26] deployed a wireless sensor network for the real-time monitoring of a perishable food chain and highlighted the need to meticulously configure both software and hardware system components to achieve technical viability and a successful data communication rate. Table 2 summarises the sensors used in real-world agrifood supply network operations, along with the parameters and monitored unit, that could enhance water stewardship.

Table 2. Categorization of sensors for water stewardship.

Monitored Parameter	Monitored Unit	Water Monitoring	References
Evapotranspiration	Crop	Direct	Sánchez-Molina et al. [34]; Incrocci et al. [35]; Fourati et al. [36]; Nolz [37]
Precipitation	Crop	Direct	Fourati et al. [36]; Nolz [37]
Soil Moisture Content	Crop	Direct	Sánchez-Molina et al. [34]; Fourati et al. [36]; Nolz [37]
Leaf Water Content	Crop	Direct	Mohara and Dutta [31]; Sánchez-Molina et al. [34]
Temperature	Vehicle; warehouse	Indirect	Wang et al. [26]
Humidity	Vehicle; warehouse	Indirect	Wang et al. [26]
CO_2 Concentration	Vehicle; warehouse	Indirect	Wang et al. [26]

Although the majority of sensors directly monitor water-related parameters in the crop field, such as evapotranspiration, precipitation, soil or leaf water content, other sensor applications could further support water management though monitoring parameters which are indirectly related to freshwater resources. Indicatively, monitoring the temperature or humidity in a fresh commodity warehouse reduces the risk of food waste [24], which otherwise could lead to further food production requiring additional freshwater resources [38]. Figure 1 provides a graphical representation of a sensor-based system for enabling water monitoring in agrifood supply networks.
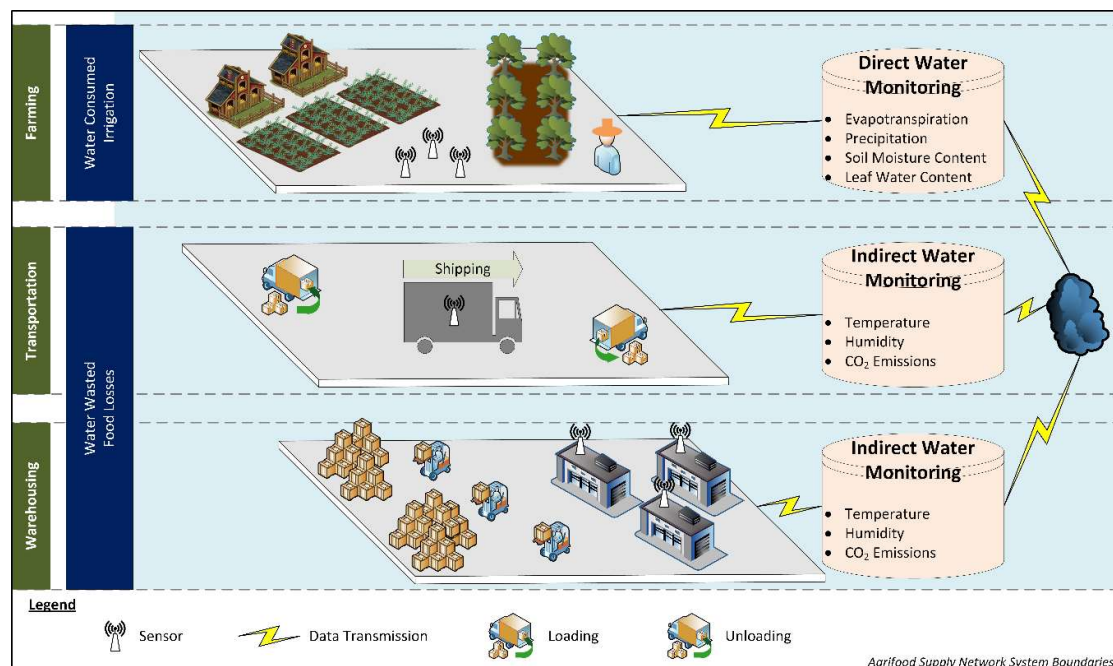

Figure 1. Sensor-based system for water monitoring in agrifood sytems.

4. Discussion

Technological advancements in the automation field allow for real-time environment sensing and data processing, thus allowing for increased responsiveness and enhanced resilience. In the agrifood sector, regardless of the size of the agricultural fields, the use of sensor-driven operations could further promote food security [39], which constitutes an emerging challenge for both developing and developed nations.

Although sensor applications for directly monitoring freshwater resources have been limited up until now, this paper constitutes a first research effort towards identifying the existing types of sensors that can be used in agrifood supply operations to support decision-making processes around automated-driven water stewardship. We envision that this work could encourage: (i) farming practitioners to apply sensor applications for efficient freshwater monitoring and management, indicatively in the case of container nursery crops (i.e., plants grown in containers in soilless substrates), to cultivate food commodities in water-scarcity-prone areas, and (ii) all stakeholders to develop a holistic sensor-based system for monitoring freshwater and other relevant parameters across end-to-end food supply networks.

Future research should investigate the ramifications of sensor applications on managing water use from a food systems perspective, as potential rebound effects fostering the expansion of the total irrigated area and associated agricultural operations could arise; hence, water consumption would be increased due to the higher irrigation requirements [40]. Finally, application of sensors for enabling water monitoring in meat-based human food [41], or even animal food [42], supply

networks could further provide meaningful insights on the sustainable use of freshwater resources in the water-intensive livestock industry.

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