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A multi-level approach to the energy-water-food nexus: From molecule to governance

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ABSTRACT

The energy-water-food (EWF) nexus is an approach to resource management that highlights the inextricable relationship that exists among three essential resources. The EWF nexus is aimed at fostering interlinkages, limiting trade-offs and exploiting synergies that exist amongst these resources. Adopting the nexus approach is key to sustainable development, as it can alleviate resource insecurities and harness collaboration between sectors. Several EWF nexus-related studies have exhaustively analysed the different levels of decision-making within the nexus. However, these studies have failed to account for the multi-level relationship that exists among the different levels of the nexus, as most have adopted a level-based approach. This review study presents a novel multi-level approach to addressing the EWF nexus-related challenges. The study analyses the multiple levels that exist within the EWF nexus. The three levels identified are the molecule, process, and governance levels. The study goes on to show how communication amongst all three levels not only impacts the performance of the system but is crucial for decision-making as the three stages are intrinsically related such that the decisions at one level directly influences the others. The study starts by reviewing the various molecular-level changes that can be made in each of the EWF resources to enhance their performance. Then a review of the set of modelling and analytical tools that have been applied to the process and governance levels are presented. Finally, a novel decision-making pyramid integrating all three levels is presented and discussed using the case of a greenhouse food production system.

1. Introduction

Over the last few years, the global population has been experiencing a significant demographic expansion owing to industrialization that has once enhanced livelihoods and living standards. However, the continuous increase in population with all that it engenders as growing demands on resources and industrial services is causing tremendous pressures on natural resources and their surrounding environment. Statistics have revealed that the global population is expected to reach a level of 9.7 billion by 2050, leading to a significant surge in demand in all major industrial sectors. Food demand is predicted to rise by 70% and global energy by more than 50%. The water sector is the major driver of the food and agriculture sector, with a share of 70% will experience unprecedented withdrawal rates to meet the requirements of other sectors. To supply sufficient resources to all sectors and feed the ever-increasing population, resource sectors should expand to accommodate the rise in production. This would cause significant pressures on the environment due to the emissions associated with energy generation, water withdrawal or treatment and food production. In addition, pressures on resource sectors and resource depletion are not the only issues caused by demographic expansion. Indeed, increased demand for food products would lead to food insecurity in many regions of the world especially ones with limited financial resources. As a response to these challenges, many efforts have been made to identify efficient solutions that can alleviate resource insecurities and harness collaboration between sectors. Part of those efforts is the Energy, Water, and Food Nexus, an approach that emphasises the intrinsic interlinkages between the three resource systems and fosters the interlinkages amongst them as a means to limit tradeoffs and exploit synergies (Hoff, 2011). In this regard, there are numerous literature review papers available in the

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context of the EWF nexus. Studies of the EWF nexus mainly focus on the potential for formulating and assessing the EWF nexus. For instance, Namany et al. (2019a) discussed the decision-making tools for the EWF nexus assessment; Mannan et al. (2018) reviewed the life cycle assessment to evaluate the nexus; Albrecht et al. (2018) focused on systematic and mathematical approaches for the EWF nexus quantification, whilst Zhang et al. (2018) discussed EWF Nexus contexts in terms of linkages and basic connections. Additionally, the challenges and opportunities for the optimisation of EWF nexus systems are reviewed by Garcia and You (Garcia and You, 2016; Zhang et al., 2019). Endo et al. (2017) evaluated the state of EWF nexus research by studying the EWF nexus regions, and stakeholders. The potential for the EWF nexus to obtain sustainable development targets was assessed by Simpson and Jewitt (2019). The review presented views on interpretations and challenges within the nexus and their optimisation potential. Recently, Endo et al. (2020) conducted a spatial-driven review of the methodologies and approaches within the EWF nexus.

Afshar et al. (2022), identified the lack of appropriate decision-making tools to evaluate different resource allocation strategies as one of the major shortcomings of the EWF nexus system. Understanding and accurately recognizing the relationships between the various elements of the EWF nexus system and their interactions can be a useful tool for managers and decision-makers to make accurate and appropriate decisions about how to address the challenges between diverse stakeholders. In a bid to create a stable relationship between the EWF resources in the nexus, Molajou et al. (2021), created simulator modules for each of the three components of the nexus (energy, food and water), and then integrated these three simulators with an optimizer to create stable relationships between the nexus system. The optimizer would help improve development indicators of social and economic welfare, aiding decision-making.

Thus far, studies on the EWF nexus have exhaustively analysed the multiple levels of decision-making within the nexus, accounting for decisions made at various levels in the nexus. Lazaro et al. (2022), highlighted that the nexus approach is evolving into an integrative approach inculcating new topics over time. They identified five trends in topic evolutions in studies on the nexus from 2012 to 2022. Among the most recent trends identified, there is an indication of the nexus being applied on different scales by adopting a circular economy principle. However, these studies have failed to account for the inter-level relationship that exists in the nexus, as most of them adopted level based perspective. This review study proposes a multi-level approach to addressing issues related to the EWF nexus systems. The study analyses the multiple levels that exist within the EWF nexus. The three levels identified are the molecule, process, and governance levels. The study goes on to show how communication amongst all three levels not only impacts the performance of the system but is crucial for decision-making as the three levels are intrinsically related such that the decisions at one level directly influences the others. The study starts by reviewing the various molecular-level changes that can be made in each of the EWF resources to enhance their performance. Next, a review of the studies that address the inter-sectoral interactions that exist within a nexus system is presented at the process level. Then a review of the set of modelling and analytical tools that have been applied to the governance levels is presented. Finally, using the case of a greenhouse, discussions on the benefits of integrating these multi-levels for maximised resource efficiency and effective decisions making is presented. Fig. 1 illustrates the structure and methodology used in this review study.

2. Review methodology

This section presents the methodology adopted in this review study. The goal of the review is to present a multi-level framework for addressing EWF nexus-related problems. To do this, three key levels are identified within the nexus framework namely;

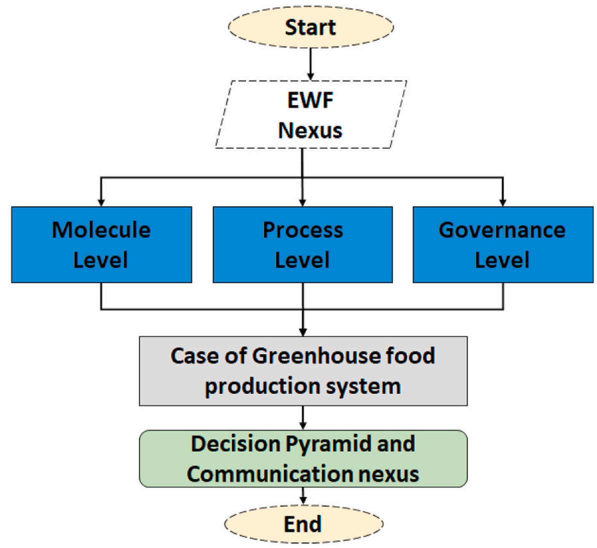

Fig. 1. Structure used in this review study.

- Molecule level – Deals with individual components or systems in the nexus. It explains how changes at the material level of a said component can improve the performance of the system.
- Process level – This is seen as the interlinkage between the various systems in the nexus. It is where all systems and subsystems are integrated to achieve predefined goals.
- Governance – At this level, decision-makers contend with regulatory policies and framework that legislates the operations at the lower levels.

These three levels influence the performance, process interactions and decision-making within the nexus. Fig. 2 illustrates the framework used in this study to develop a decision pyramid. The third section of this study discusses the molecule level. Here a review of nanomaterial applications in sustainable food/agricultural production, water and energy sectors is presented. The goal is to show how at the material level resource enhancement can be achieved for all three resources. Section four presents a review of some of the process-level studies conducted on EWF nexus-based systems. The review addresses the inter-sectoral interactions that exist within a nexus system. Here studies related to the laws of thermodynamics are covered as well as how concepts such as exergy and emergy can be used in the optimisation of whole processes.

The governance and policy level review is presented in section five. Here a review of the multi-scale, multi-objective and multi-uncertainties challenges of the nexus and tools by which to deal with them are reviewed. Finally, a novel decision-making pyramid integrating all three levels is presented and discussed using the case of a greenhouse food production system.

2.1. Research methodology

The search for articles was done using the largest abstract and citation database *Scopus*. Keywords are used as “inclusion criteria” to limit the number of results from the title, abstract and keywords returned in the search. Screening of the results is done to determine if an article is relevant or not based on the author’s knowledge and experience.

Some of the keywords and phrases used in the search include; *energy-food-water nexus, energy nexus, water nexus, food nexus, energy optimisation, nanomaterials, nanomaterials in water, nanomaterials in energy systems, nanomaterials in food production, EWF in process integration, EWF in governance, hi-tech greenhouse* and *decision-making tools* to name a few. These keywords are dependent on the sub-topic being reviewed.

The period selected for the literature search was 2010–2022.

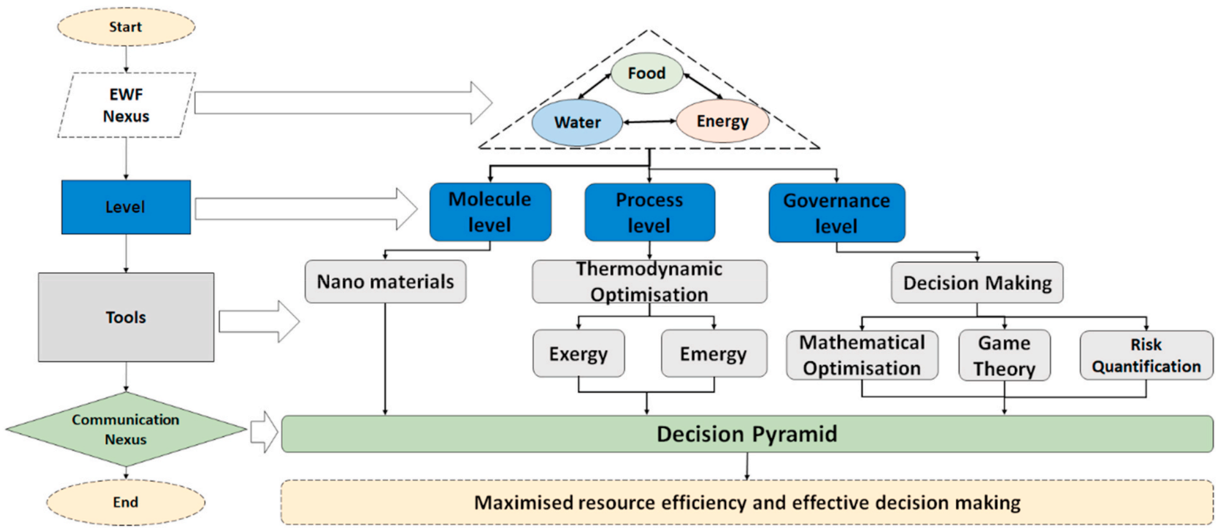

Fig. 2. Framework used in this study to develop a decision pyramid.

However, a few vital studies relevant to the discussion, but outside the time range was also added to the study.

3. Molecule level

The molecule level is the smallest unit in the process or system. It is where physical, chemical or biological interactions that can influence the system's performance are seen. At the molecule level, we take a look at the materials used in the system and see how they affect the system's overall output. An example of molecule-level changes that can influence the nexus performance might include material selection or the addition of nanomaterials. Nanomaterials are materials between the scales of 10-100 nm. Numerous studies have shown the potential of these materials to significantly influence the individual components of the EWF nexus (Okonkwo et al., 2021a). In this section, a review of some of the applications of nanomaterials as it relates to the food, water and energy components of the EWF nexus is presented and discussed.

3.1. Nanomaterials for sustainable food/agriculture production

The application of nanomaterials in the agricultural sector is less explored than its counterparts in the water and energy sectors, despite this, the combination of agriculture and nanomaterials/nanotechnology has proven to be highly effective in improving agricultural productivity. Thus, in this section, we present an overview of the applications and opportunities presented by nanomaterials in increasing agricultural production and its influence on the energy and water components of the nexus. These applications include; the application of nano-sensors for enhancing nutrient and pest management, targeted delivery of agrochemicals and the direct application of nanomaterials.

Nano-sensors have a wide range of applications in agriculture since they can detect soil pH, insecticide, toxins, herbicide, temperature, water or moisture content, pesticides and pathogens. As such, nano-sensors present a significant opportunities for water, energy and agrochemical savings and can also increase agriculture productivity (Farahi et al., 2012). Nano-sensors are characterized by their ability to employ the unique physical and chemical properties of nanomaterials, in particular, their high surface area to volume ratio and active surface functional groups in the ability to explore pathogens, chemicals and nutrients (phosphates and nitrates) (Sekhon, 2014). This helps in regulating pathogen management by injecting the required amount of nutrients through precision farming rather than what is currently used. Different nanomaterials such as silver, gold, silicon and carbon nanotubes (CNTs) were used to fabricate nano-sensors for specific applications. For example, silicon nanoparticles were used for the detection of gram-negative bacteria *Xanthomonas axonopodis* which was found in *Solanaceae plants* (Sekhon, 2014). Gold and silver nanoparticles not only improved the detection limit of melamine, perchlorate, *Salmonella*, pathogens and viruses, but they also provided faster detection signals for Surface-Enhanced Raman Scattering (SERS) (Duncan, 2014). CNTs were utilized for analytes (pathogens, bacteria) detection in food and agriculture. Single-wall CNT biosensors were found to have high sensitivity toward some bacteria found in food products such *as Staphylococcus aureus* bacteria (Choi et al., 2017) and the gram-negative bacteria *Yersinia enterocolitica* (Sobhan et al., 2019). Moreover, CNTs were investigated for pesticide detection to regulate their application. CNT biosensors can detect Monocrotophos (Bin et al., 2018) and Diazinon (Rahimnejad et al., 2019) which are well-known used pesticides for pest control and prevent high concentrations that might be transferred to human use. An increase in agricultural yield as a result of the application of suitable nano-sensors decreases the water requirements for the plants while increasing productivity.

There are huge quantities of fertilizers used in agriculture, and unfortunately, large amounts of them run off into the soil, which leads to pollution of surface and groundwater (Prasad et al., 2016). Add to that the unmanaged use of pesticides leads to high levels of leaching into the soil and spreading to the environment. Nanotechnology has proposed many solutions for the **targeted delivery of agrochemicals** by encapsulation (Rahman et al., 2016). Encapsulation effectively holds the nutrients and regulates their release into the plants (Patra et al., 2017). This makes the fertilization process stable, more effective and leads to the achievement of a sustainable release of nutrients. Nano-encapsulation of fertilizers can be done by different means, i) fertilizers can be coated by a thin film of nano-materials, ii) fertilizers can be encapsulated in a porous nano-material, and iii) fertilizers can be supplied to plants on a nano-scale (Rai et al., 2012; Wang et al., 2016). Encapsulated nitrogen by porous zeolites has proven to be a better strategy for nitrogen release (Manikandan and Subramanian, 2014). Chitosan and kaolin nanocomposites possess very good properties for the sustainable release of NPK fertilizers (Tarafdar, 2014). Nitrogen encapsulated into urea-modified hydroxyapatite nanoparticles is a stable and slow-release nitrogen fertilizer (Kottegoda et al., 2018). Several other studies have reported the successful slow release of nitrogen fertilizers by encapsulation in zeolites, halloysites, bentonites and montmorillonites (Schmid and Stoeger, 2016; Saharan et al., 2013; Rossi et al., 2014). Mesoporous silica nanoparticles were also recommended for encapsulating or absorbing large amounts of agrochemicals since they can be produced with tunable outer particle diameter and tunable pore size (Wang et al., 2016). Pesticides have also been encapsulated into nanoparticles, and polymer or lipid-based encapsulation and this process found to prevent the early degradation of the active components of pesticides against pests. Moreover, encapsulation offers the monitored release of pesticides for long periods (Rahman et al., 2016). Chitosan and alginate beads were also proposed and investigated for pesticide encapsulation (Kashyap et al., 2015). Silica nanoparticles were used to encapsulate pesticides like avermectin, and porous silica provided the slow release of the pesticide and prevents it from photodegradation (Li et al., 2007; Pérez et al., 2010; Kumar et al., 2014). CNTs and citric acid have also shown promising results in monitoring pesticides (Pandey, 2020). More examples of the application of nanomaterials such as zinc, silver, titanium and others for targeted delivery of agrochemicals are available in these references (Khot et al., 2012; Luiz et al., 2014; Durán and Marcato, 2013; Ghormade et al., 2011; Davidson and Gu, 2012; Roy et al., 2014). Therefore, the slow release of fertilizers and pesticides by encapsulation rather than the conventional soluble release method led to a decrease in the loss of agrochemicals, economic savings, decrease environmental pollution, increase production rates of crops and decrease energy and water consumption.

In the **direct application of nanomaterials**, some nanomaterials such as titanium, copper, silver, silicon, cerium and aluminium have shown multiple benefits by applying them directly to plants. For example, the treatment of maize with TiO_2 nanoparticles has led to an increase in the growth rate of the plants, this was attributed to the enhancement of photo energy transmission and absorption of light (Moaveni and Kheiri, 2011). The biomass production of Canola plants was increased by the addition of CeO_2 nanoparticles (Rossi et al., 2016). Moreover, the addition of CuO has led to an increase in the productivity of eggplants, this was attributed to the antimicrobial characteristics of CuO that improve the resistance of the eggplant to soil fungi (Elmer and White, 2016). Other nano-materials were used as nutrients, where they are either sprayed on the plants or infused into the soil. For instance, zinc nanoparticles have increased the growth rate of different plants such as tomato leaves (Rosa et al., 2013). Iron oxide nanoparticles have increased the grain weight and protein content of wheat plants (BHJana, 2018). Furthermore, chitosan nanomaterial was found beneficial for the slow release of some enzymes required for plant growth (Dayarathne et al., 2019). Feregrino et al. (Feregrino-perez et al., 2018), concluded that other nano-materials such as boron, manganese, molybedium, zinc, and copper were very important for the growth of plants. So far, the literature has demonstrated the benefits of molecular-level changes to food yield. The use of nanomaterial as sensors or in fertilizers has the potential to improve the EWF nexus in terms of decreasing water and energy consumption while increasing the food production yield.

3.2. Nanomaterials for water treatment

Water treatment is a very energy-intensive sector, and improving the sectoral efficiency of this process can decrease the amount of energy required for its processes. Various traditional techniques have been used in wastewater treatment, such as precipitation, screening, anaerobic and aerobic treatments, distillation, coagulation, reverse osmosis, electrodialysis, filtration, evaporation and adsorption (Almanassra et al., 2020a). However, most of these technologies depend on large operating systems, which require high costs of energy and engineering expertise (Das et al., 2017). The advancement in nanotechnology and nanomaterials have been employed to improve the performance and effectiveness of traditional water and wastewater treatment methods. What distinguishes nanomaterials in water treatment applications is their finite size $\leq$100 nm, diversity, high surface area, strong sorption of contaminants, high adsorption capacity and fast dissolution (Rodrigues et al., 2017). Other advantages of nanomaterials include a high recovery rate of water, improved pollutants removal selectivity in membranes and adsorption, reduced consumption of energy, decrease membrane fouling rates and they have a great potential for resource recovery such as nutrients (Almanassra et al., 2020b; Jiuyang et al., 2013; Katherine et al., 2009). Various nanomaterials such as metal oxide nanoparticles, carbon nanotubes (CNTs), graphene-based materials, carbon nanofibers, cellulose nanoparticles, nano polymers, chitosan nanoparticles were widely used for water treatment applications (Chella et al., 2016).

Adsorption is a widely used water treatment process, adsorption is considered an easy process, provides fast removal and is effective at low concentrations of pollutants (Ning et al., 2021). Adsorption is a surface removal process in which water pollutants are attracted to the surface of the adsorbent (Almanassra et al., 2021a). Nanomaterials have been used as nano-adsorbents for the removal of different pollutants. Due to their small size, high porosity, high surface area and active surface groups; nanomaterials can provide high adsorption capacity and strong binding capacity with pollutants (Chella et al., 2016; Bhaskar et al., 2016). Nanomaterials can adsorb pollutants with different i) speciation behaviour, ii) hydrophobicity and iii) molecular sizes (Das et al., 2017; Kunli et al., 2016). Nanomaterials have also great potential for resource recovery. For example, agricultural wastewater streams are usually loaded with nutrients from fertilizers and other organic compounds. Nanomaterials under special conditions such as high selectivity and well-designed reversibility mechanism can be utilized to recover nutrients and hence reuse these chemicals (Almanassra et al., 2021a). Among the different nanomaterials used in the adsorption process, carbonaceous materials (CNTs, carbon nanofibers, graphene, and activated carbon), metal oxides and metal nanoparticles were widely emplyed in the adsorption process (Almanassra et al., 2021b). These materials have been shown to have a fast and high adsorption capacity for the removal of heavy metals, nutrients, emerging pollutants and other organic and inorganic pollutants (Sahar et al., 2015). For better recovery and selective removal of the desired pollutant, the carbonaceous materials can be modified with different nanoparticles for a targeted process such as modifying the surface of CNTs with iron, magnesium, lanthanum, aluminium and calcium nanoparticles for the removal of phosphate from aqueous solutions (Almanassra et al., 2021a, 2021b).

The membrane filtration process is a mechanical treatment process in which water streams are pressurized to pass through a membrane to be purified. Membrane technologies are the most widely used technologies for water treatment. Different membrane technologies are used for water treatment such as nano-filtration (NF), reverse osmosis (RO), macro-filtration (MF), distillation and electrodialysis. Despite its many uses, the membrane filtration process suffers from different problems such as fouling, it is an energy-intensive process, requiring constant cleaning and replacement, fixed solute selectivity and low recrudescence (Das et al., 2017; Chella et al., 2016). As such, nanomaterials were incorporated into membranes fabrication to decrease the fouling rates, produce new geometries of membranes, produce membranes that are more resilient and enhance the perm-selectivity of membranes which in turn has improved the water recovery rates and decreased energy consumption (Siavash, 2020). Carbonaceous materials, metal and metal oxide nanoparticles as well as zeolites and ceramics were of significant interest to improve the membrane performance (Zheng-Yang et al., 2020). CNT-modified membranes have 10 times more permeability than RO membranes (Das et al., 2017). Graphene-modified membranes have higher salt rejection than other membranes (Yi et al., 2016). The selectivity of heavy metals removal by membranes was also improved by graphene oxide-modified membranes (Zhiqian and Shi, 2016). Carbonaceous materials were incorporated into the formulation of nano-ceramic, nano polymeric and nano-zeolite membranes to improve their retention and selectivity (Yanbiao et al., 2020).

Nanomaterials were employed for water treatment in other applications such as antimicrobial agents (Emmanuel et al., 2020), disinfection (Zheng-Yang et al., 2020), photocatalysis (Xueying et al., 2021), and sensing and monitoring (Ali et al., 2020). The scientific knowledge of water treatment by nanomaterials is increasing exponentially. More discussions and clarifications of nanomaterials in water treatment can be found in the following references (Das et al., 2017; Chella et al., 2016). It should be noted that in all cases discussed, the use of nanomaterials improved the process and has a high tendency to decrease energy use in the water treatment process.

3.3. Nanomaterials for energy systems

Nanomaterials can be applied in both conventional and renewable energy systems. These applications have helped improve or enhance energy production. Nanomaterials have found applications in thermal energy storage, solar technologies and oil and gas exploration (Okonkwo et al., 2021b). In the **oil and gas sector**, nanomaterials have the potential to improve the operations of exploration, production and refining of crude as well as decrease the cost of these processes. By using nanomaterials as a contrast agent for sensitivity measurements, drilling operations can be improved (Krishnamoorti, 2006). It can also enhance the cutting fluids used in drilling operations by reducing tool wear and operating temperature which can lead to reduced water loss (Gerken et al., 2014). Also, studies have shown that nanomaterials can be applied in the exploration, monitoring and surveillance of reservoir morphology (Turkenburg et al., 2012; Kapusta et al., 2012). For enhanced oil recovery, nanomaterials can improve the adsorption, oxidation and gasification processes (Banerjee, 2017). These applications are expected to decrease the carbon footprints associated with the industry (Rosen et al., 2005).

In **thermal energy systems**, nanomaterials have found applications in heat exchangers, vapour compression cooling, and thermal energy storage amongst other systems. In **heat exchangers**, nanomaterials have been seen to enhance the rate of heat transfer between fluids. This is because nanomaterials enhance the thermal conductivity of the fluids leading to an increase in the rate of absorption and thus an improved rate of heat transfer (Hajatzadeh Pordanjani et al., 2019; Qi et al., 2019; Moradi et al., 2019). In a double tube heat exchanger, TiO_2-water increased the heat transfer rate by up to 14.8% (Qi et al., 2019), Al_2O_3-water by 16% (Mohankumar et al., 2019) and multi-walled carbon nanotubes (MWCNT) by 35% (Moradi et al., 2019). In other heat exchangers, significant heat transfer augmentation has been observed when using nanomaterials, a 20% increase was observed when using nanoparticles in plate heat exchangers (Variyenli, 2019), while in the shell and tube heat exchanger, a 41% enhancement was observed when using Al_2O_3-water (Ullah et al., 2019). **Cooling and heating** machinery are an integral part of everyday life as they help in the thermal management of spaces by making them conducive for humans, animals and plants (greenhouses). Nanomaterials have shown tremendous potential to improve the heat transfer and energy-saving potentials of refrigeration and heating ventilation and air conditioning (HVAC) systems (Okonkwo and Al-Ansari, 2021).

Nanomaterials could be used in the refrigerant (nano-refrigerants), as lubricants (nano-lubricants or nano-oil) or/and as secondary fluids in the chilled water loop. As nano-lubricants nanomaterials showed a higher degree of subcooling at the condenser exit and improved coefficient of performance (COP) by 6.5% (Nair et al., 2020). Nano-lubricants can also assist in decreasing the pressure losses and power consumption in the system (Bhattad et al., 2018). As nano-refrigerants nanomaterials can enhance COP by as much as 12.2% using Al_2O_3 nano-refrigerants (Jeyakumar et al., 2019). It has the potential to improve the boiling and condensation heat transfer coefficient which could lead to more compact vapour compression units (Bhattad et al., 2018). In the secondary fluid used in district cooling, the use of nanomaterials can lead to a 5.3% improvement in the refrigeration effect and a reduction in the compression ratio (Ahmed and Elsaid, 2019). Nanomaterials can also lead to a reduction in pump power consumption and an increase in the COP of the system (Ahmed et al., 2018; Alawi et al., 2015). These system improvements in cooling and heating devices can lead to savings in energy consumption.

Nanomaterials can be used in **thermal energy storage** for both latent and sensible heat storage. Nano-encapsulated phase change materials (nePCM) have been suggested to improve the thermal properties of phase change materials traditionally used as storage mediums (Bondareva et al., 2019; Navarrete et al., 2019). These new nePCM can increase the phase change enthalpy and latent energy storage capacity by up to 17.8% (Navarrete et al., 2019). The use of SiO_2 in capric fatty acids increased both the thermal conductivity and specific heat capacity of nePCM and hence increase the sensible heat storage capacity of the fatty acid (Martín et al., 2019). Nanomaterials have been widely suggested for application in solar energy systems. Studies have shown that they can be applied in both photovoltaic and concentrated solar thermal systems. In photovoltaic thermal systems (PVT), nanomaterials can be used to cool the temperature of the solar cells, thereby enhancing the electrical output of the system. Using Al_2O_3–ZnO-water nanofluids, the cell temperature decreased by 21% and yielded a 34% overall enhancement in the collector's performance (Wole-osho et al., 2020). Similar enhancements were witnessed with the use of carbon allotropes, like 19.5%, 15.24% and 9.46% increases in overall efficiency were observed for graphene nano-platelets water, MWCNT-water and SWCNT-water nanofluids respectively (Alwan Sywan Alshaheen et al., 2020).

In **solar thermal collectors**, nanoparticles have demonstrated in many studies the ability to enhance heat transfer and improve the overall efficiency of the collector. In a study by Abdullatif et al. (2021), adding copper nanoparticles to thermal oils used as heat transfer fluids in a parabolic trough collector (PTC) can enhance the thermal efficiency of the system. In another study, a 34.5% enhancement in thermal efficiency was recorded when using TiO_2-water in the PTC (Tayebi et al., 2019), while a 15% enhancement was recorded when using Al_2O_3--Therminol in the PTC (Norouzi et al., 2020). Similar results have been seen in other collectors like the flat plate collector, where the addition of nanomaterials enhanced the collector's efficiencies (Wole-osho et al., 2021; Okonkwo et al., 2020). A thermal efficiency enhancement of 22% for TiO_2-water (Sacithra and Manivannan, 2019) and 21.5% for $CeCO_2$-water (Michael Joseph Stalin et al., 2019), was seen with the addition of nanoparticles. Also in the evacuated tube collector, a 23% enhancement was recorded with WO_2-water (Sharafeldin and Gróf, 2019), 13.8% with CuO-water (Peng et al., 2020) and 26.7% with Ag/EG-water (Kaya and Arslan, 2019). Similar enhancements were witnessed in the linear Fresnel reflector where a 1% enhancement was recorded when using CuO-syltherm oil (Bellos et al., 2019). In all solar collector applications, the energy yield is increased at no cost of additional water required for the process.

From this section, we see that molecular level changes can influence systems performance and by extension the overall nexus output. These little changes, weather with crop yield, freshwater production or improved energy performance can have a cascade effect on the overall nexus and hence, both social-economic and environmental benefits are attainable. This highlights the need for interactions between decision-makers (governance) and processes, with the process level accounting for intra-process interactions between the macro and molecular level effects that can further enhance the overall EWF nexus performance.

4. Process level (improving inter-sectoral interactions)

Interactions within a system play an essential role in the quantification of process efficiencies and in improving inter-sectoral interactions. At the process level of the EWF nexus, it is important to understand the laws of thermodynamics and their relationships between different flows.

4.1. Thermodynamics and the EWF nexus

Inside any system or process, the destruction of resources occurs through waste generation in addition to the useful product output. The destruction of resources is based on the second law of thermodynamics which relates to entropy and exergy concepts (Bakshi et al., 2011). The first law indicates that energy can neither be created nor destroyed, but can only change in its form which means that every system in any state has a property called energy. In nexus optimisation studies, both laws of thermodynamics are required to comply with each other to enhance efficiency by minimising entropy and exergy destruction (Nižetić et al., 2019). Depending on the scale of the problem different approaches have been used such as optimisation tools, exergy analysis, and emergy analysis. Optimisation within the EWF nexus system can be obtained by minimising the exergy destruction or entropy production. EWF nexus optimisation tools must be applied in three steps; process integration, inter-linkages optimisation, and overall EWF nexus system optimisation. The main objective of nexus optimisation is to reduce the input raw materials and minimize the destructions within the system. As mentioned previously, these different approaches depend on the scale of the problem. Starting from a single component or process to the whole system optimisation, the approach can vary (Fouladi and Al-Ansari, 2021). To assess the efficiency of the integrated system, multiple indicators such as exergy and emergy efficiencies can help decision-makers reach more sustainable solutions. This section summarizes the main research works that have been done on different process optimisation within the nexus.

4.2. EWF nexus performance evaluation

As mentioned earlier, EWF nexus optimisation must be started from single processes and technologies within the system. Energy integration and optimisation is the most common method which has been studied in the literature for different energy, water or food technologies. Jia et al. (2019) analysed the water-energy nexus of a power generation sector using the graphical pinch technique. An enhancement in the economic performance and environmental impacts was achieved for energy-water utilization. For the simultaneous integration of energy and water, Liu et al. (2015) developed a novel approach using pinch analysis. The proposed method captures the trade-off between the use of utility and freshwater consumption and showed the application for larger industrial problems. Gabriel et al. (2016) integrated a desalination unit process with a net surplus of heat energy from other processes to show the synergy between the water-energy nexus. The authors developed the mathematical formulation with the pinch analysis for the optimized superstructure considering different scenarios. For large-scale problems, multiple objectives are required to be considered for the overall system to obtain the optimized solution and help the decision-makers to select the most sustainable solutions (Al-Thani et al., 2020).

Fouladi et al. (2021) proposed an optimisation problem to integrate the EWF nexus within an eco-industrial park (Fouladi et al., 2021). Ning and Fengqi (2020) proposed a multi-objective optimisation model for the energy-water-food-waste nexus to address the environmental concerns during the COVID-19 pandemic. Pareto front curves were used to capture the trade-offs between the different objectives and the results showed that food waste disposal can decrease by almost 38% through the nexus system. Using a multi-objective optimisation methodology, Zhang and Vesselinov (2017) captured and quantified the trade-offs between the economics, resources, and their environmental impacts. Cansino-Loeza and Ponce-Ortega (2020), presented an EWF nexus multi-objective optimisation model which satisfies different stakeholders involved. It was shown that water reuse results in a significant improvement within the nexus and is crucial for sustainable development. Chamas et al. (2021) developed and validated a model for EWF nexus resource management at the regional scale. The proposed model provided optimum resource allocation strategies for the multiple scenarios considered. Garcia and You (2015) presented an optimisation model for a biofuel system that includes environmental and economic objectives. A mixed-integer non-linear fractional programming coupled with a life cycle assessment was applied to quantify the nexus.

There are numerous studies on the optimisation of the processes within the nexus boundaries (Al-Ansari et al., 2015). Al-Ansari et al. (2017) studied an EWF nexus system by considering a biomass-integrated gasification combined cycle combined with a carbon capture unit. The syngas produced out of the manure utilization were used in a cycle to generate power. AlNouss et al. (2019) optimized a biomass gasification unit among the EWF nexus. Different technologies were applied for the gasification process to get the most sustainable one. Li et al. (2020) proposed an optimisation approach to produce sustainable bioenergy in the food sectors by water-energy resource allocation. Furthermore, the approach was able to capture the trade-offs and help decision-makers to identify the units which need more improvement. As shown from the above studies, depending on the scale of the problem pinch analysis and multi-objective optimisation approaches can be used to integrate the processes and systems for a defined EWF nexus framework.

To evaluate the performance of an EWF nexus system, different thermodynamic efficiency approaches are applied. Exergy and emergy analysis are the most common ones in the literature. Based on the second law of thermodynamics, exergy is a measure of available energy (Rosen and Bulucea, 2009). The exergy analysis helps to identify the most inefficient units within the system by identifying components with the highest exergy destruction rates (Marquet, 1991). Exergy destruction is linked to the entropy generation in a process. Therefore, any optimisation aims to minimize the exergy destruction and entropy production. For resource management, exergy analysis is commonly applied since it can quantify the extent of energy, water, and food resource depletion within a defined system. This method can be used for the performance evaluation of process sub-systems and the overall system. Many studies in the literature use exergy efficiency to calculate the overall system performance by quantifying the input and useful output flows. Khattak and Greenough (2018) showed that within the EWF nexus system, wastewater flows have the highest exergy destruction. Therefore, the addition of a water treatment unit resulted in a 4.1% reduction in resource utilization. In terms of the energy-food nexus, Cruz et al. (2017) assessed the production of fuel from a type of biomass generated by the food sector and showed that the gasification process has the largest destruction of exergy accounting for almost 50% of the total. Similarly, Li et al. (2019) proposed an exergetic life cycle assessment to evaluate the environmental impacts of a hydrogen production unit using the biomass gasification process. Results indicated that hydrogen produced using biomass has more environmental benefits as compared to natural gas. Altmann et al. (2019) compared different desalination technologies by quantifying the exergetic efficiency corresponding to each one. It was shown that reverse osmosis has the best performance by having the least exergy destruction. For the overall EWF nexus system, Leung Pah Hang et al. (2016) used a minimum cumulative exergy technique to optimize the resource consumption for a defined EWF nexus system. The work solved a local case study in Whitehill and Bordon using the proposed approach and showed how the optimisation of sub-systems affects the overall performance. In general, multi-generation systems are gaining significant attention as they produce different outputs such as energy and water, which can serve EWF purposes. Exergy analyses are mainly used in multi-generation systems to evaluate overall performance. For example, Luqman and Al-ansari (2020) proposed a multigeneration system that produces water, air, and electricity. The system is based on renewable energy sources such as solar energy, wind, and biomass. Using the thermodynamic assessment, it was found that the highest exergy destruction rate was in the biomass combustion unit, which resulted in an overall system exergy efficiency of nearly 18%. Furthermore, Safari and Dincer (2019) developed a new multi-generation biomass-based integrated system. To evaluate the performance, the exergy analysis was used and the overall exergy efficiency of the systems was found to be almost 63%.

The second thermodynamic approach that has been applied to the EWF nexus studies is the emergy analysis. The methodology is similar to energy and exergy, except that all products and services are equivalents of solar energy using their solar transformity coefficient (Odum, 1996).

Multiple eco-efficiency emergy indicators exist which can evaluate the resource efficiency and environmental impacts associated with a specific process (Liu et al., 2018). After reviewing the literature, it was found that emergy analysis is mainly applied separately to sub-systems of the EWF nexus system. For instance, Taskhiri et al. (2011) compared the water network of individual plants and the industrial park by adding a water reuse option based on an emergy model. The results showed that by network optimisation the total emergy reduces from 4.50 to 4.34 sej per hour which is the result of wastewater treatment and reuse. In the food sector, Liu et al. (2014) performed an emergy-based simulation on multiple aspects of two agriculture farms such as resource consumption, economic, and environmental impact. Similarly, Lewandowska-Czarnecka et al. (2019) compared two groups of agriculture farms based on both energy and emergy analysis and showed how the emergy approach accounts for a larger set of inputs. In the EWF nexus field, Wang et al. (2017) used a modified emergy analysis to study an integrated framework. The results identified the agriculture and water production units to have higher energy intensity. de Freitas Bueno et al. (2016) proposed multiple biofuel production units from biomass waste utilization and used the emergy indicators to assess resource management.

Process level interactions are important to the performance of the overall system and optimizing the process level can improve the overall performance of the EWF nexus and also improve intersectoral relationships.

5. Governance and policy enhancement (improving inter-sectoral and intra-sectoral interactions)

The use of the term "governance" as it relates to the EWF nexus, has expanded over the years and has been approached from several dimensions, including integrative and cooperative governance, economic governance, risk and resource security governance and environmental system governance to name a few (Urbinatti et al., 2020). In this study, the term governance is used as an umbrella concept for integrated decision-making within the nexus. It refers to the body responsible for intersectoral decision-making within the nexus. Benson et al. (2015), viewed the overlapping of decision-making possibilities as the main constraint to nexus governance.

Enhancing the individual efficiencies of the EWF nexus systems and sub-systems is crucial to improving the performance of the overall nexus and maximising the outputs of its underlying systems. Materials level changes can be highly effective in increasing the productivity of water, energy and food sectors by upgrading the functionalities of current technologies and providing novel solutions to issues associated with the three resources, including but not limited to water contamination, enhanced energy efficiency and detection of pathogens in food production. In addition, the existing literature has demonstrated that the performance of the EWF nexus could be further amplified by harnessing the process-level interlinkages between the three nexus systems as a means to balance tradeoffs and exploit synergies. However, achieving a holistic and improved nexus efficiency implies the consideration of other numerous internal and external factors that are not necessarily captured at the level of processes and operations. Nexus systems operate in unsteady and uncertain environments ruled by diverse policies and legislations that have an impactful influence on their overall performances along with their inter-sectoral and intra-sectoral interactions. In addition, when assessing the nexus, it is crucial to investigate the relationship between sectors across all levels of decision-making. In this regard, the modelling of the nexus should dynamically illustrate the effect of individual processes on high-level decisions, such as investments and regulatory decisions, while considering the effect of those decisions on individual performances and systemic interactions.

To design, model and enhance the performance of the EWF nexus system comprehensively external and internal challenges governing the three sectors and their underlying interlinkages should be modelled adequately. Internal factors consist of the inter-sectoral and intra-sectoral competitions between and amongst systems stemming from the diverse objectives and multiple stakeholders involved, while external issues represent the multiple risks and uncertainties imposed by the surrounding environment, counting the anthropogenic and natural influences. The following section summarizes the modelling techniques used to account for the aforementioned challenges and advises decision-making in the EWF nexus sectors as means to complement the enhancements conducted at the operational and process level using nanomaterials and process optimisation. Each tool reviewed in the subsequent section is addressing one or two multi-scale challenges of the nexus, accounting for multi-stakeholders, multi-objectives, and multi-uncertainties.

5.1. Optimisation models for EWF nexus systems governance

The EWF nexus involves a variety of systems and subsystems requiring different inputs and necessitating diverse investments. The need for this ongoing planning is to ensure continuous and well-founded decision-making to assess strategies and potential enhancements in the systems. Optimisation models represent one of the commonly used tools to assist decision-makers in taking optimum and efficient decisions. Optimisation can be used to represent real-life problems requiring the selection of the most beneficial alternative amongst a set of choices under constrained circumstances (Gill et al., 2019). In the context of the EWF nexus systems, optimisation was widely utilized in improving the operations and processes within resource systems (Garcia and You, 2016), by tackling technical aspects such as optimizing the thermal efficiency of membranes used in water desalination systems (Duong et al., 2015), increasing crop yields through the optimisation of nutrients intake (Lahlou et al., 2020), or enhancing the storage capacity of power production plants (Guédez et al., 2014). Alternatively, optimisation was also proven beneficial in tackling and advising higher-level decisions involving strategic planning and multi-disciplinary governance. Particularly, this tool is deployed to address the multi-scale challenges that govern nexus systems either internally or externally, counting the divergent objectives and multiple uncertainties. Resource systems are comprised of several subsystems and industries striving to achieve similar or antagonistic goals that might engender conflicts if tradeoffs and synergies are not adequately managed. The nexus literature offers a myriad of studies addressing the issue of multiple objectives using optimisation frameworks. In this regard, multi-objective optimisation is a type of multi-criteria decision-making (MCDM) method that aims to balance targets amongst and within nexus sectors as a means to maximise payoffs (Gal, 1980), hence alleviating any conflicting targets. Considering the governance level, this tool is usually adopted in instances involving the interference between several disciplines aspiring for several goals, such as achieving social, economic and environmental efficiencies. Namany et al. (2019) adopted a multi-objective optimisation model to enhance the self-sufficiency level of a food system while minimising the environmental and economic costs associated with the EWF nexus configuration in charge of food production (Namany et al., 2019b). Similarly, Chen et al. (2020) utilized the same tool to design a holistic framework that harnesses the interactions between the three nexus systems for a collective benefit, while minimising the environmental burden associated with their operations. The model suggests some sustainable decision-making recommendations that foster EWF systems collaboration within a low-carbon economy (Chen et al., 2020). Intending to improve the agricultural system as part of the food security target, Rajakal et al. (2020) adopted a fuzzy multi-objective optimisation solved using a mixed-integer linear program (MILP) to plan the expansion of an agricultural system including the production land, facilities and logistical operations of the agro-industry, to maximise economic benefit while minimising the water and carbon footprints (Rajakal et al., 2020). With a particular emphasis on the energy and water nexus, Al-Obaidli et al. (2019) utilized multi-objective optimisation to conduct a portfolio analysis aiming to determine the optimal cogeneration configuration of water and energy technologies. The model investigates the deployment of renewable and non-renewable energy systems in energy and desalination cogeneration plants while aspiring for a minimal levelized cost and environmental emissions (Al-Obaidli et al., 2019). In an attempt to identify the power structure within the EWF nexus from a water governance perspective, Samaneh et al. (2020), using an MCDM-based model ELECTRE 1 for social network analysis of water governance, identified the public sector as holding much of the power and are the main key actor in nexus decision making, and should dictate the type of policies in each of the sectors.

In a world buffeted by uncertainties and randomness, there is a need to design models that accommodate the perpetual changes in systems. For EWF nexus sectors, particularly, uncertainties are a major challenge that hampers decision-making. Whether they are related to systems' operations and interlinkages or inflicted by changes in the surrounding environment, risks and uncertainties should be adequately accounted for to generate realistic and efficient optimal results (Namany et al., 2019a). Stochastic and robust optimisation are some of the most used types of mathematical optimisation techniques that take into consideration variability and uncertainty while generating optimal solutions (Govindan and Al-Ansari, 2019). Stochastic optimisation is used when the model parameters are not deterministic and vary according to a probabilistic pattern, while robust optimisation is one of its sub-categories, where the problem involves extreme uncertainties (Hemmi, 2017) (Shindin et al., 2014). In the context of the EWF nexus, Ji et al. (2020) adopted a multi-stage stochastic fuzzy random program (MSFRP) to manage a complex EWF nexus system under deep uncertainty. The model aims to optimize the overall system benefit by balancing profits and risk tolerance from the perspective of decision-makers. The benefit of each nexus system is represented by the strategic planning of energy supply, allocation of water resources and the distribution and cultivation of agricultural land. The different scenarios are formulated based on diverse water availability conditions and climate change uncertainty (Ji et al., 2020). Focusing on a small-scale EWF nexus system Karan et al. (2018) deployed a stochastic model that takes into account stochasticity in energy flows for a small household. The purpose of the proposed optimisation is to determine a cost-efficient and sustainable nexus system that meets the demands of the household from the three resources (Karan et al., 2018). Adopting a robust optimisation based on metamodels, Beh et al. (2017) proposed a methodology that hedges against deep uncertainty associated with population variability and climate seasonality while planning and designing a water-supply system (Beh et al., 2017).

5.2. *Risk quantification in volatile environments*

The multi-uncertainty challenge is one of the most critical issues affecting the decision-making process within the EWF nexus. The ever-changing nature of resource systems along with the increasing economic and industrial activities give rise to many risks and volatilities that impact the accuracy of results generated by conventional steady nexus models. Climate seasonality, sudden natural disasters, price volatility due to market turmoil, as well as political instabilities, are all factors disturbing the performance of the three sectors. To alleviate systems changes and discrepancies, there is an incumbent need to implement mitigation plans and adaptation strategies to cope with systems while considering uncertainties. Stochastic and robust optimisation is often used to model and improve systems in instances involving randomness and uncertainties; however, risks should be quantified, first, before they are used as input parameters in optimisation models (Haji et al., 2020). There exists various categories of risk assessment, quantification and prediction models that are complementarily used with optimisation models as part of the nexus literature to represent systems dynamically and realistically and enhance their adaptive capacity. Monte Carlo simulation is one of the commonly adopted methods to model risks and uncertainties and predict outcomes under volatile conditions (Harrison, 2009). Kadigi et al. (2020) applied Monte Carlo simulation to assess the economic viability of the project deploying advanced technologies and improved rice-farming techniques. Scenarios were evaluated while considering the risk associated with the preference of policy-makers vis-à-vis the suggested practices (Kadigi et al., 2020). Adopting the same technique, Govindan et al. (2018) predicted the behaviour of energy prices generated from different renewable and non-renewable power generation plants and represented findings using a normal distribution (Govindan et al., 2018). Results were later used by Namany et al. (2019) to conduct a stochastic multi-objective optimisation that determines the optimal energy and water mix driving a food system under the stochasticity of gas prices (Namany et al., 2019b). Along with Monte Carlo simulation, artificial intelligence and particularly, artificial neural networks, are another modelling tool extensively demonstrated in the literature regarding risk assessment and uncertainty prediction, especially in large-scale problems involving multi-faceted systems. Unlike simulation techniques wherein the model is known beforehand and uncertainty is resulting from unknown variables, in neural networks, the source of uncertainty resides in the relationship between input variables which are predefined (Chen et al., 2019). Woldesellasse et al. (2018) adopted a neural network to process satellite images of the Alfalfa crop and predict its water demand. The results of the neural network are used in Mixed-integer Non-linear programs (MINLP) to maximise crop productivity (Woldesellasse et al., 2018).

5.3. *Game theory for intra-sectoral and inter-sectoral competitions*

The multi-stakeholder characteristic is one of the central features of the EWF nexus that challenges the efficient modelling of its systems and subsystems. The diverse entities involved in operating the nexus sectors and their associated industries have divergent objectives, which more often result in competing interests and conflicts. Competition in the context of the EWF nexus can be witnessed at the level of inter-sectoral or intra-sectoral interactions. An example of intersectoral competition can be represented by the striving of the food and energy sectors to access water. While water resources are the main drivers of agricultural activities through the irrigation process, water is also essential for the cooling of power generation plants. Both sectors depend on the same resource to function and maximise their profits, therefore conflict that might arise due to this competition could potentially hinder consistent access to water resources, which would consequently lead to operational delays and economic losses (Hua et al., 2020). As for intra-sectoral competition, it can be observed within the sectors themselves, either at the governance level between the government and project holders, between different technologies or industries producing or performing similar activities such as farms, or amongst different sectors such as private and public (Scott et al., 2001). To account for these two types of competition within and between nexus systems, game-theoretic approaches are used to model competitive parties (Garcia and You, 2016). In this regard, Motalleb and Ghorbani (2017) proposed a decision-making guideline, based on a game theory approach, to assist energy sellers under diverse market constraints wherein competition is modelled as a Stackelberg non-cooperative game (Motalleb and Ghorbani, 2017). Adopting the same game, Namany et al. (2018) proposed an optimisation model that identifies the most environmentally friendly and economically viable configuration of water and energy technologies to meet a food production target, while being constrained by a non-cooperative competition between two power plants (Namany et al., 2018).

6. Case study: Greenhouse

The case study illustrated in Fig. 3 demonstrates the potential of optimising the performance of the greenhouse in terms of energy consumption and reduction in waste thermal energy. The decision variables

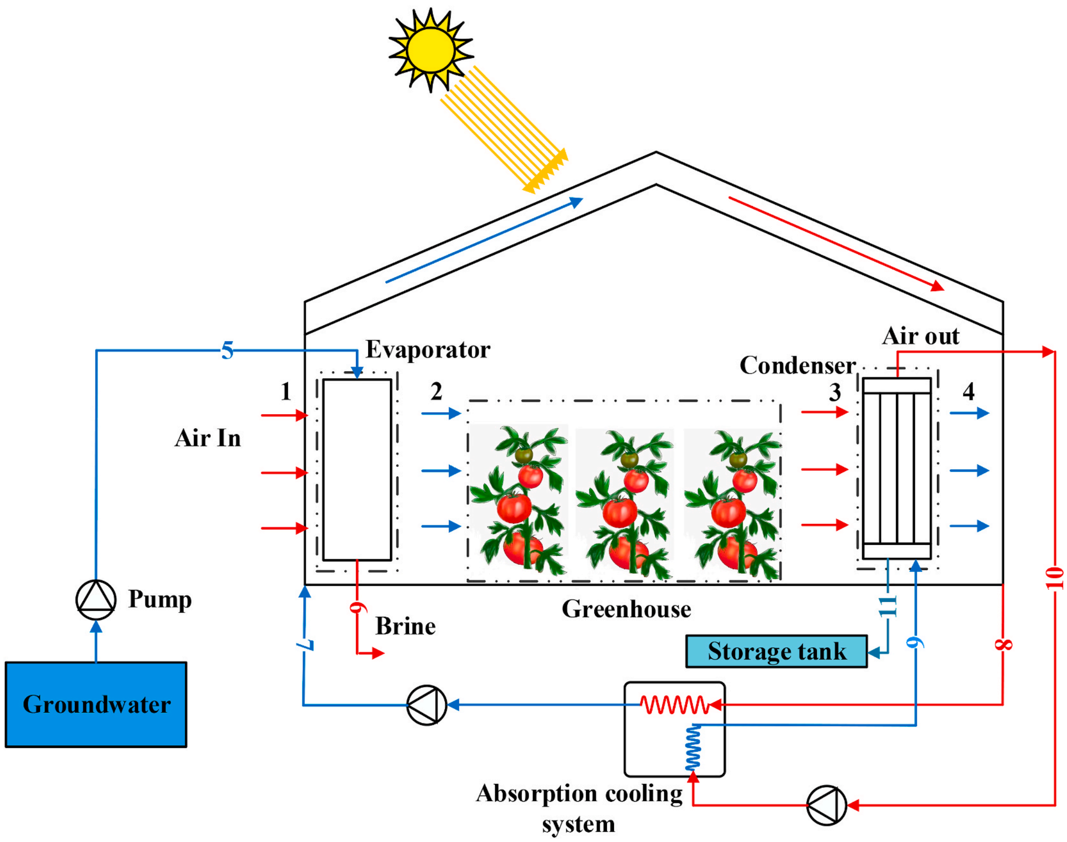

Fig. 3. Schematic of the greenhouse.

affecting the performance of the greenhouse in the present study include the greenhouse roof covering material and cooling system used to provide the optimum temperature to the plants. The choice of a cooling system is important as it affects the energy input to the system and exergy destruction by the system.

The greenhouse operates on the humidification-dehumidification (HDH) process of ambient air. HDH-based greenhouses are suitable for arid climates with scarce water and high temperatures as they can produce cooling and water by utilizing saline groundwater. Ambient air enters the greenhouse at (point 1), where it passes through an evaporative cooling pad. Saline groundwater is pumped to the evaporator (point 5), where latent heat of the air is absorbed as evaporative cooling occurs. The air temperature drops as it removes part of the saline water and achieves a saturation state. After the evaporator, the chilled air (point 2) passes through the plantation area of the greenhouse to remove the heat entering the greenhouse due to solar irradiance and high ambient temperature. The air absorbs the greenhouse heat and water vapours in the form of plant evapotranspiration as the temperature of the air rises (point 3). The air is pulled across a condenser installed at the other end of the greenhouse to extract water from the air (point 4). The fluid temperature flowing through the condenser is lower than the wet-bulb temperature of the air, and condensation occurs, which is stored in the tank and can be later used for irrigating the crops (point 11).

6.1. Molecule level

At the molecule level, nanofluids are utilized in two closed-loop cycles in the greenhouse-roof, and condenser components. Nanofluids are passed through the greenhouse roof (point 7), where they absorb part of the incident solar radiation, resulting in a lower cooling load inside the greenhouse. The temperature of the nanofluid rises as it passes through the roof and heat gained is utilized to operate the absorption cooling cycle system (ACS) (point 8). After exchanging heat with the ACS, the closed cycle is complete, and the nanofluid flow back into the greenhouse roof. To enhance the heat exchange process, the nanofluids are passed through the condenser (point 9) to further reduce the temperature of the air flowing through the greenhouse. After absorbing the heat, the nanofluids flow into the evaporator of the ACS (point 10), where heat exchange with the refrigerant occurs.

The greenhouse is a good example of an ecosystem where resources of the EWF nexus are needed for effective food production. At the molecular level, the use of nanomaterials is seen to benefit energy consumption and freshwater production. For the energy needs of the greenhouse, nanofluids serve as a solar spectrum filter when used on the roof of the greenhouse. This is because nanofluids can absorb radiations having a wavelength greater than 1400 nm, leaving the greenhouse cooler. According to a study by Sajid and Bicer (2021), such applications of nanofluids in greenhouses have the potential to reduce the required cooling load in the greenhouse space by 26% (Sajid and Bicer, 2021). The use of nanofluids in the condenser increases the rate of heat extraction from the system, this can lead to a 23.3% reduction in the total work input of the ACS (Okonkwo and Al-Ansari, 2021). Also, the condensate water used for irrigation is obtained as air is pulled across the nanofluids flowing through the condenser installed at the other end of the greenhouse. Such material changes have a significant impact on the process-level interactions of the system and can even lead to enhanced performance if properly optimized. However, as earlier stated, achieving a holistic and improved nexus efficiency implies the consideration of other numerous internal and external factors that are not necessarily captured at the processes level.

6.2. Process level

At the process level, as mentioned earlier numerous methods can be used to minimize resource consumption. Energy optimisation of the overall system can be achieved by optimizing small units. For example, in the illustrated greenhouse case study, the energy consumption of the greenhouse can be optimized by reducing the amount of solar radiation entering the greenhouse. External or internal shading screens can be used to block solar radiation, but they also reduce the photosynthesis active radiation (PAR) entering the greenhouse, which impacts negatively crop yield production (Mahmood et al., 2018). However, liquid flowing through the greenhouse roof absorbs part of the incident thermal energy and reduces the overall cooling load. Utilizing spectrum-splitting nanofluids which absorb the near infra-red radiation (NIR) and allow PAR, can significantly reduce the cooling load and energy consumption (Abdel-Ghany et al., 2012). Therefore, using the pinch analysis, the minimum cooling load will be decreased. Furthermore, to enhance the system performance, the thermal energy absorbed by the flowing liquid can be used for multiple purposes (i.e., absorption cooling). Consequently, the exergy efficiency of the overall system will be improved. The other decision variable considered in this case study is the type of cooling system used to provide optimum conditions to the plants. The different cooling systems such as fogging and misting, vapour compression refrigeration systems (VCRS) and absorption cooling system (ACS) have their operating requirements. Fogging and misting require a large amount of water, which is unfeasible for arid climates with a scarcity of freshwater. VCRS requires high-grade energy such as electricity to operate the compressor, which increases the system's overall energy consumption. In comparison, ACS requires a small amount of energy to operate the pumps. Furthermore, ACS can operate on low-grade thermal energy such as waste energy from an exhaust, which in turn reduces the overall thermal waste and improves the exergy efficiency of the system. Hence, the trade-off analysis using multiple-objective optimisation problem are capable of capturing the synergies among different resources. As it was shown, starting from a small unit such as cooling systems, energy optimisation can enhance the unit's function while affecting the overall system performance by capturing the trade-offs among them. Exergy and emergy efficiencies are further calculated to indicate the overall impact.

6.3. Governance level

At the governance level issues regarding the environmental challenges of nanomaterial disposal and the health concerns of possible spillage of nanomaterials into the crops all represent risks and uncertainties imposed on the system. In this case, environmental and safety regulations must be accounted for while considering the effect of those decisions on the system's performance. In addition, decisions made at the process level of a particular sector require a consideration of the situation of other nexus systems that oil the wheel of its operations. For instance, before modifying individual processes as part of the food sector, there is an incumbent need to assess the influence of such decisions on the energy and water requirements, the cost of acquiring those resources and any other repercussions that could potentially arise. The interdependence between the EWF nexus creates an unbreakable bond amongst the sectors leading to inherent correlations between decisions undertaken, regardless of the decision-making level. In this regard, decision-making can be divided into three different levels, which are inherently connected. The molecular level, which comes at the bottom of the pyramid, can be defined as the smallest unit constituting a system (Fig. 4). It is the building block that controls the operations of the different system's components which consequently affects the overall system's performance. At this level, the decisions made would be based on running experimental work, where various materials are investigated. The process level, which constitutes the middle stage is considered the fundamental step where all systems and sub-systems are integrated to achieve a predefined target. This would include the thermodynamic aspects and the linkages amongst existing flows, counting energy and materials. The decisions at this level would be based on conducted assessments and thermodynamic analyses. At the higher level of the pyramid, decision-making consists of legislating rules and policies

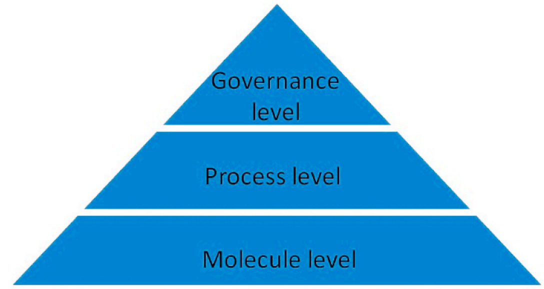

Fig. 4. Multi-level decision-making pyramid.

that would regulate the operations and management of the subsequent levels. In the context of EWF nexus systems, the various levels are both connected at the inter-sectoral and intra-sectoral levels. Intra-sectoral connections influence the decisions made within one particular system. An example of this relationship can be depicted by the impact of using certain nanofluids in the power production system, which is a molecular-level decision, on the selection of the type of power generation component which is process level decision. As for inter-sectoral interactions, they reflect the impact of decisions made within a nexus system on the other two sectors across the three levels of the pyramid.

The energy-water-food nexus is a multifaceted concept involving diverse actors and linking multiple systems and sub-systems. The decision-making pyramid is an interesting framework to consider when addressing any system's performance as it can capture the synergies and tradeoffs that emerge from the inter-sectoral and intra-sectoral links between EWF nexus systems. As seen in Fig. 5, the pyramid is the communication tool that ensures the flow of information between the three levels in each of the EWF nexus sectors. In real-life, policies and governmental decisions regulate the operations between systems that constitute the process level. Similarly, the process level coordinates the molecular-level decisions by providing guidance and assistance in the selection of the material type. All these sectorial interactions occur while sectors are exchanging resources and information. This top-down relationship between levels can also help address the multi-scale challenges that govern nexus systems either internally or externally, by accounting for the divergent objectives and multiple uncertainties.

7. Conclusions

This study points out the multiple levels of performance and

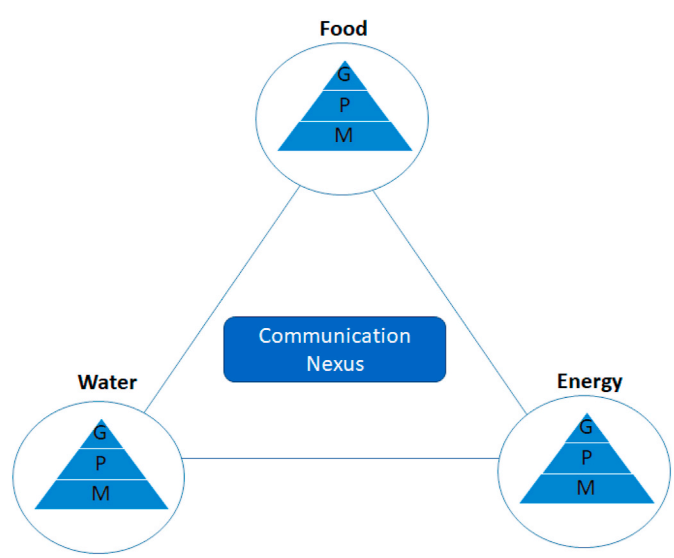

Fig. 5. Decision-making pyramid as a communication nexus.

decision-making that exist within the EWF nexus system. The study highlights the molecule level as the level where material changes can be highly effective in increasing the productivity of water, energy and food sectors by upgrading the functionalities of current technologies. The process level interlinkages as where synergies are harnessed for better system integration and the governance level is where other numerous internal and external factors not necessarily captured at the process level but legislate the operation of the lower levels are decided upon. This study integrates all three levels into a decision pyramid that captures the synergies and tradeoffs amongst them to demonstrate that the performance of the nexus can be further amplified by harnessing said pyramid as a communication tool that ensures the flow of information amongst the diverse entities involved in operating the nexus sectors and their associated industries. By doing so, it becomes easier to investigate the relationship between sectors across all levels of decision-making.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: NA.

Data availability

No data was used for the research described in the article.

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