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Sustainability transitions of urban food-energy-water-waste infrastructure: A living laboratory approach for circular economy

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ABSTRACT

Urban areas often face versatile stressors (e.g., food security, congestion, energy shortage, water pollution, water scarcity, waste management, and storm and flooding), requiring better resilient and sustainable infrastructure systems. A system dynamics model (SDM), explored for the urban region of Orlando, Florida, acts as a multi-agent model for portraying material and energy flows across the food, energy, water, and waste (FEWW) sectors to account for urban sustainability transitions. The interlinkages between the FEWW sectors in the SDM are formulated with multiple layers of dependencies and interconnections of the available resources and their external climatic, environmental, and socioeconomic drivers through four case studies (scenarios). The vital components in the integrated FEWW infrastructure system include urban agriculture associated with the East End Market Urban Farm; energy from the fuel-diverse Curtis H. Stanton Energy Center; reclaimed wastewater treated by the Eastern Water Reclamation Facility, the Water Conserv II Water Reclamation Facility, and stormwater reuse; and solid waste management and biogas generation from the Orange County Landfill. The four scenarios evaluated climate change impacts, policy instruments, and land use teleconnection for waste management in the FEWW nexus, demonstrating regional synergies among these components. The use of multi-criteria decision-making coupled with cost-benefit-risk tradeoff analysis supported the selection of case 4 as the most appropriate option as it provided greater renewable energy production and stormwater reuse. The SDM graphic user interface aids in the visualization of the dynamics of the FEWW nexus framework, demonstrating the specific role of renewable energy harvesting for sustainably transitioning Orlando into a circular economy.

1. Introduction

Population growth and migration, economic development, and climate change continuously reshape the evolutionary pathway of many urban infrastructure systems. Globalization and urbanization not only create environmental impacts but also increase resource demand for sustainment and growth. These activities result in various environmental impacts, including the increase in greenhouse gas (GHG) emissions (Rosa and Dietz, 2012), exacerbation of the urban heat island effect (Debbage and Shepherd, 2015), ecosystem degradation (Levin et al., 2020), waste disposal (Ikporukpo, 2018), water pollution (Nath et al., 2021), nonpoint source pollution via stormwater runoff (Ma et al., 2018), and land-use and resources competition (Barthel et al., 2019). Facing such global change impact, it is vital to understand the interdependencies and interconnections among the four sectors (food, energy, water, and waste) in a nexus framework and to optimally manage water, food, and energy resources, and mitigate their (negative) impact on the environment. This is more critical since the initial analysis of a typical food, energy, water (FEW) nexus may not be sufficient to incorporate all the elements represented in their interconnections, which tend to exclude waste. These traditional interrelationships in food, energy, and water sectors missed the emphasis of waste streams, as it is impractical to produce, distribute, and consume food, energy, and water without waste generation (Garcia and You, 2017). A system dynamics model (SDM) can portray material and energy flows across the FEW nexus. Thompson et al. (2021) used various modeling approaches such as agent-based modeling and climate dynamics in an urban FEW nexus, emphasizing food production to explore sustainability and resilience. Wa'el A et al. (2017) conducted a SDM for the demand assessment of FEW and the generation of wastewater and organic waste at household scale. The FEW nexus approach has been expanded to include other sectors and variables to address sustainability; for instance, the Food-Waste-Water-CO_2 nexus has also been explored to study the impacts of urban sustainability (Xu et al., 2020). Recently, an

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ecosystem service with optimization was evaluated for a FEWW nexus applied to the New York State bioenergy production by Garcia et al. (2019); additionally, Zhao and You (2021) explored the use of a FEWW nexus for New York State during the COVID-19 pandemic to address increased waste generation, which was coupled with energy generation. Yet, little research has thoroughly evaluated food, energy, water, and waste (FEWW) nexus via SDM to account for urban sustainability transitions under climate change impact. It is thus essential to consider and explore the complex feedback systems in integrating the four sectors of an urban FEWW nexus in this study.

The interlinkages between the FEWW sectors are numerous, with multiple layers of dependencies and interconnections associated with the available resources and their external climatic, geopolitical, and socioeconomic drivers. These entities can affect a nexus, as policymakers and stakeholders play an essential role in developing various urban FEWW nexuses via various public-private partnerships that coexist multiple layers of interactions and behaviors of distinct entities (Zellner et al., 2008). However, there is a disconnection between the governance structure and function affecting these sectors due to the uncoordinated nature of policies among the sectors (Weitz et al., 2017). As such, the proposed nexus analysis in this study involves managing the interrelations and tradeoffs in the four sectors through the implementation of policy instruments and the analysis of cost-benefit-risk tradeoffs. Hence, a risk-based transformation of critical urban infrastructure systems regarding food security, energy resilience, water sustainability, and cleaner production under global change impact requires either bottom-up or top-down decision-making processes, or even both (i.e., a hybrid mode).

If a metropolitan region is considered a living organism, then the overall mass and energy flow with intensive interactions in a FEWW nexus can be described by urban metabolism and employed to evaluate the metropolitan development of a city and suburban/rural environment. This viewpoint can advance our understanding of the social, physical, and environmental factors that influence the adaptive transformations of critical urban infrastructures at a regional scale. Thus, bottom-up or top-down decision-making processes can be coupled to elucidate the FEWW nexus where the resources flow and resource links related to water, energy, nutrients, and waste materials can be concatenated (Kennedy et al., 2007). This nexus expansion can help realize the criticality of system planning for infrastructure transformations via a living laboratory and aggregate resource links and their robustness in response to climatic, economic, environmental, and social changes. The proper integration of multi-agent modeling and multicriteria assessment can help investigate possible evolutionary pathways of urban FEWW infrastructure systems in complex and dynamic environments.

The aim of this study is thus to construct and evaluate an urban FEWW nexus at a regional level by considering sector-based synergies across a suite of planning alternatives associated with operational cost-benefit-risk factors under uncertainty. Practical implementation was assessed by analyzing the criticality of the emerging FEWW nexus in Orlando, Florida in the United States (US) to improve the understanding of the adaptive transformation of urban farming supported by both renewable and nonrenewable energy sources and water reclamation/reuse plans under changing environments (e.g., climate change impacts). In this study, the impacts of the FEWW system and the interactions among the agents/actors can be observed via SDM to support the roles of multiple stakeholders (e.g., government, private, non-profit organizations, and/or state actors) influence on decision making. The four sectors of the FEWW nexus include two water reclamation facilities, one stormwater management agency, one energy generation facility, one municipal landfill, and a set of urban farms to close the loop in a circular economy. Cost-benefit-risk assessment for four planning scenarios via multicriteria decision making was carried out to determine order preference according to the similarity to the ideal solution (TOPSIS). The cost-benefit-risk tradeoff in support of TOPSIS provides a lucid and centralized decision-making process with a risk assessment to prioritize what is important in future infrastructure expansion according to public and private entities. The synergies and interactions among sectors in a FEWW nexus can contribute to sustainable development goals that can address many resource links such as energy from waste, waste for food, water for energy, water for food, etc., in a circular economy. The research questions to be answered include: 1) How does the landfill gas recovery in a FEWW nexus contribute to a circular economy in the Orlando community? 2) Can a well-formulated SDM analysis help policy and decision-makers allocate and prioritize resources using multicriteria decision analysis? 3) What resource limitations are faced in a FEWW nexus in terms of water resilience, food security, and energy sustainability? 4) Will this FEWW infrastructure system respond to the impacts of climate change? 5) Can a FEWW nexus system help decrease the carbon and water footprints?

2. Infrastructure system components in an urban FEWW nexus

The area of Downtown Orlando is described by the US Department of Agriculture (USDA) as a food desert, where the community is void of fresh food within an 8 km (5-mile) radius. The USDA defines a food desert as an area characterized by low income and limited transportation, where the population has limited access to supermarkets or grocery stores in accordance with census tracts (Dutko et al., 2012). Usually, a 1 km^2 area is selected to measure food access, and then the grid size is increased. Low access is determined when at least 33% of the population or 500 people live more than 1.6 km (1 mile) from supermarkets or grocery stores in urban regions. In congruence with limited access to fresh food, West Orlando is also a low-income area. Fig. 1, obtained from (USDA, 2021), helps visualize the low-income and low access sectors (food deserts) in Orlando, according to 2019 census data and the distribution of the FEWW components in the Orlando area. The overall depiction of the low-income, low-access, and food deserts in Orange County is shown by different color scales area-wide (Fig. 1). The corresponding facility ID, address, and latitude/longitude location are summarized in Supplementary Information Table S1. Further, the light blue color in the map reflects the low-income regions where the family income is less than 80% of the median family income in a metropolitan area or state. In addition, the light pink represents a lack of access to fresh food or market for 33% of the population within a 1.61 km (1 mile) radius. Therefore, all the infrastructure components should be evaluated for integration to facilitate fresh food production, encourage social, economic, and environmental sustainability, and promote urban resilience in a FEWW nexus. The interconnections within a FEWW nexus in the urban area can be further assessed by the concept of urban land teleconnection since it links distant geographical areas with coincident changes in the environment from urbanization (Güneralp et al., 2013).

The infrastructure system within the FEWW nexus located in Orlando, Florida, encompasses the interrelated material and energy flow between the East End Market Urban Farm (EEMUF), energy production from the Stanton Energy Center (coal, natural gas, landfill gas, and solar photovoltaic (PV) from solar farms), Eastern Water Reclamation Facility (EWRF), Water Conserv II (WCII) Water Reclamation Facility, Water Conserv II Distribution Center (WCIIDC), and Orange County Landfill (OCL). For more detail, refer to Supplementary Information Table S1 for the corresponding facility ID, address, and latitude/longitude locations. As such, the proposed infrastructure system in the FEWW nexus contains interlinkages and interdependencies across the four sectors, including resources links of food-energy, waste-energy, water-food, energy-food, water-energy, and waste-food, where all of the facilities form mutual relationships or partnerships with at least one of the outputs/flows used as the input for another in the system (Fig. 2). The purpose of formalizing this nexus is to transition the original fragmental interactions to a closed system to take advantage of the possible interdependencies in a circular economy. The four sectors in the FEWW Nexus can be summarized as:

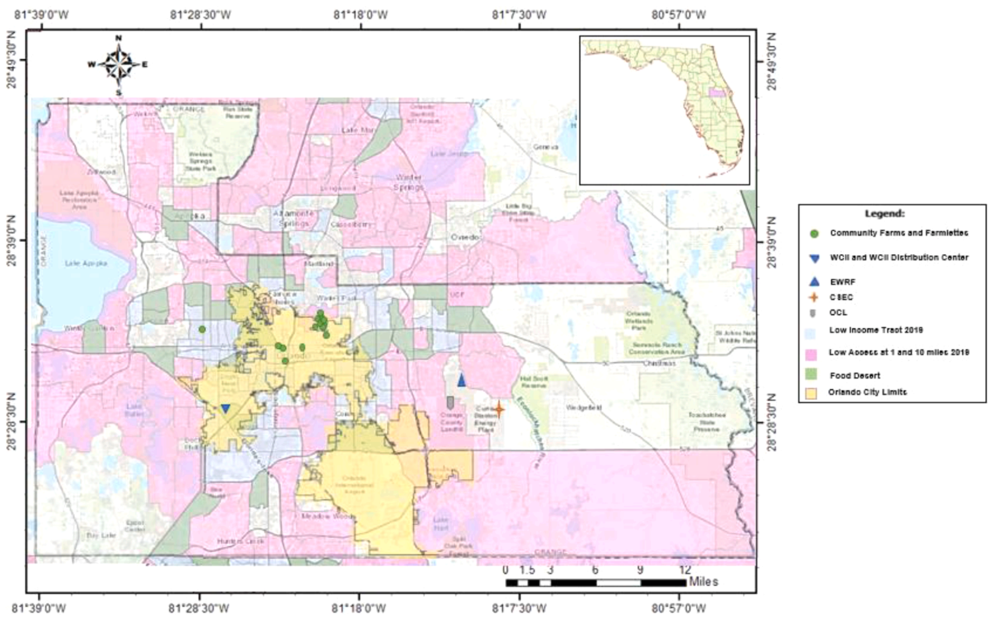

Fig. 1. Distribution of low income, low food access, and food desert (USDA, 2021) in the Urban FEWW nexus components in Orlando, Florida, including the East End Market Urban farm (EEMUF), solar photovoltaic (PV) energy production from the Curtis H. Stanton Energy Center (CSEC), Water Conserv II (WCII), and Eastern Water Reclamation Facility (EWRF) (green color is an overlap of a food desert and low-income areas) and visualization of a low-income food desert in Orlando, Florida (Source: retrieved from USDA according to 2019 data).

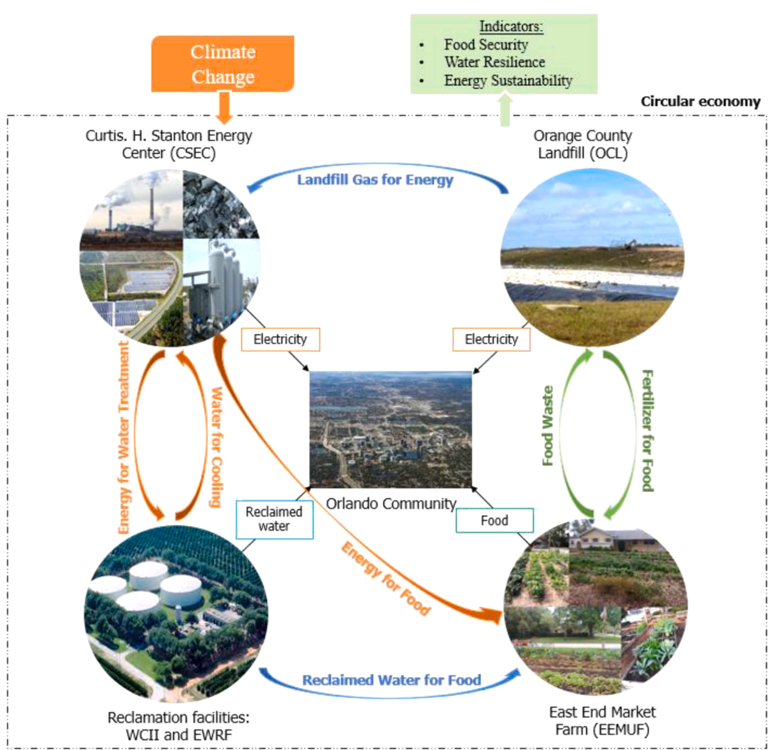

Fig. 2. Visualization of interactions and interdependences of each FEWW nexus agent.

1) *Urban Agriculture*

The EEMUF, managed by the Fleet Farming organization, consists of a total of 17 farmettes (farm sites) that utilize available front or back-yards of homes with an area of around 50–70 m^2, and six community gardens comprising a total approximate area of 2,500 m^2 distributed in Orlando, Florida. According to Fleet Farming ® agriculture program, 5140 locals were fed with a total produce harvested of 3,497 kg (7710 lb) (Fleet Farming, 2021). This is a typical top-down approach, using a governance structure with the aid of a centralized farmer market for food supply chain management. The cultivated food is available for the individual owner of the house or the community, as is the case of community gardens. A summary of the possible crops harvested and annual production in the EEMUF is described in Supplementary Information Table S2. Drip irrigation is employed at the farm sites with specified irrigation durations and events during the day. The compost is obtained from Monterey Mushrooms, Inc., situated in Zellwood, Florida, even though composting is performed at some of the farm sites as a supplementary source.

1) *Energy Generation*

The Curtis H. Stanton Energy Center (CSEC), part of the Orlando Utilities Commission (OUC), supplies energy to the Orlando region. CSEC utilizes coal, natural gas, landfill gas, and solar power for energy production, producing 940 MW from coal, 940 MW from natural gas, 47 MW from Orange County and Holopaw Landfill gas, 6 MW from Solar Farm I, and 13 MW from the Kenneth P. Ksionek Community Solar Farm (Orlando Utilities Commission, 2020a). In addition, CSEC has a 5.9 MW solar PV array consisting of about 25,000 PV modules (Orlando Utilities Commission, 2020b). A combustion residual storage area is located in the facility to store fly ash and resultant scrubber sludge.

1) *Reclaimed Water Management and Stormwater Reuse*

There are two facilities in the FEWW nexus responsible for reclaimed water management. The Water Conserv II (WCII) Water Reclamation Facility has a capacity of $9.46(10)^7$ L•d^{-1} (25 MGD), with a "zero-discharge" goal proposed to utilize the effluent for irrigation and aquifer recharge (Orlando, 2021b). The biosolids produced from the wastewater treatment process (e.g., sludge) are treated into Class A and land-applied per code B0006. Per 40 CFR Part 203 biosolids rule, both Class A and Class B biosolids can be land applied; however, only Class A is available for distribution and can be comparable to any fertilizer (USEPA, 1999). On the other hand, biosolid fertilizer could be banned by several states as well, given the increase in contaminants of emerging concern in wastewater that are challenging to eliminate (Lapen et al., 2018) which can prompt more a stringent requirement of biosolid minimum pathogen and vector attraction reduction requirements (USEPA, 1999). Therefore, biosolid fertilizers were not used for urban farming in this study due to possible secondary contamination. Additionally, WCII supplies treated reclaimed water to the Water Conserv II Distribution Center (WCIIDC) located adjacent to WCII for effluent distribution. The WCIIDC has a permitted flow of $3.06(10)^8$ L•d^{-1} (80.9 MGD) and is responsible for the distribution of reclaimed water for citrus irrigation and 32.37 km^2 (8000 acres) of rapid infiltration basins (RIBs) and citrus groves. The second reclamation facility is the Eastern Water Reclamation facility (EWRF). The EWRF has a capacity of $9.08(10)^7$ L•d^{-1} (24 MGD), treating municipal wastewater and landfill leachate from the Orange County Landfill. The effluent discharge of reclaimed water consists of wetlands and surface discharge (24% to Little Econlockhatchee river, 67% to wetlands), and 9% for local reuse (Howards, 2017). The biosolids produced in the treatment are landfilled and transferred to a residual management facility (RMF). For stormwater reuse, above-ground storage using wet detention ponds with a total area of 40,000 m^2 is incorporated.

1) *Solid Waste Management*

The Orange County Landfill (OCL) can receive Class I and Class II material, of which it receives 861,825.5 tonne•y^{-1}. The facility has a two-leachate collection, treatment, and disposal system. The leachate collected from Class I solid waste is transferred to the EWRF for further treatment. The second treatment is a collection and treatment system and a stormwater management system that provides reused water for CSEC for cooling and discharge to the Wide Cypress Swamp Wetland Treatment System (WCSWTS) (FDEP, 2020). The produced compost from yard waste with appropriate quality for agricultural use is available for public use and collection. A landfill gas-to-energy facility in the OCL transports methane to the CSEC to the coal-fired generation units via an 8 km (5 mile) pipeline (OUC, 2011). The landfill gas produced from the landfill cells is primarily collected for distribution to the CSEC for steam turbine operation and co-fired with coal, while a portion of the landfill gas is flared onsite.

2.1. Urban food-energy-water-waste FEWW nexus framework

The synergistic interactions and interdependencies in the FEWW nexus include: 1) utilization of reclaimed water from EWRF and treated leachate from OCL to CSEC for the cooling towers (water-energy nexus), 2) supply of reclaimed water from EWRF and WCII to EEMUF for irrigation (water-food nexus), 3) solar energy from CSEC to operate EWRF and WCII (energy-water nexus), 4) energy from CSEC supplied to the utility grid for urban farm irrigation (energy-food nexus), 5) landfill gas from OCL to CSEC for energy generation (waste-energy nexus), 6) food waste from EEMUF to OCL for compost production and landfill gas generation (food-waste nexus). These interactions are visualized in Fig. 2, where the allocation and utilization of the waste flow from one agent are used as an inflow for another agent, forming a closed-loop system. Further, Table S5 helps visualize the relationships in the FEWW nexus.

2.2. System analysis for an urban FEWW nexus

As previously mentioned, the case study of the FEWW nexus was conducted for the urban region of Orlando, Florida, with a population of over 287,000 (Bureau, 2019). The case study will be divided into four scenarios (cases) for evaluation in order to advance the adaptive integration of technology hubs in different conditions. Case 1 consists of the base analysis, encompassing the food, energy, water, and waste sectors with the corresponding facilities at present mentioned above. Case 2 analyzes the increase in urban agriculture and change with respect to the food sector while maintaining the framework from Case 1. Case 3 builds upon the expansion of urban agriculture from Case 2 based on policy change of land management and proposes an increase in solar energy from the policy implementation of additional incentives for solar PV farms to decrease the carbon and water footprints. Lastly, Case 4 implements a climate change scenario for more stormwater reuse and recycling, including future climate change impact associated with increased rainfall on the given Case 3 condition. According to the Intergovernmental Panel on Climate Change (IPCC), Florida will experience more extreme rainfall events and droughts with 10%−20% rainfall increase projections depending on the emission scenarios (Kirtman et al., 2017). In summary, the goal in the progression of the four cases is to address land management, incentivization for solar energy, climate change impact from increase rainfall, observe the sustainable transition of the nexus, and explore the possible tipping point and policy instruments. Thereby, these four cases show a series of planning alternatives for expansion during the next 10-year period. Table 1 describes the different components in the four scenarios of this study.

3. Methodology

This study comprises a series of integrative analyses, as demonstrated by the flowchart in Fig. 3. First, SDM is performed to address the material and energy flows in the food, energy, water, and waste sectors in which subsequently the circular economy (address many resource links) and sustainability and resilience can be explored. The involvement of cost-benefit-risk tradeoff proceeded by policy and governance, and lastly, multicriteria decision making is conveyed.

3.1. System dynamics modeling

The SDM portraying the material and energy flows in the food, energy, water, and waste sectors in the urban FEWW nexus utilize STELLA 10.0 software. The SDM supports multi-agent modeling analysis, a multi-stage planning process that corresponds to the four-scenario analyses of Cases 1, 2, 3, and 4 to visualize urban agriculture, climate change impact, and the effect on urban areas sustainability. Variables such as food production, food waste, irrigation water demand, reclaimed water supply, and energy generation is considered and explored in the technology hub integration modeled by stocks and flows to reflect resource interdependencies and interconnections. The SDM inputs and

Table 1
Case Study Description of the Current Urban FEWW Nexus.

Scenario	Analysis	Food Components	Energy Components	Water Components	Waste Components
Case 1	*Base (current condition)*	• Farm sites located in North and North-West Orlando • Area of 2500 m^2	• Curtis H. Stanton Energy Center (e.g., Natural gas, Landfill gas, Coal, Solar PV)	• Eastern Water Reclamation Facility (EWRF) • Water Conserv II Water Reclamation Facility (WCII WRF)	• Orange County Landfill • Compost Production
Case 2	*Increase in urban agriculture*	• Expansion of urban farm sites in North-East and South-West of Orlando • Area of 5000 m^2	• Curtis H. Stanton Energy Center (e.g., Natural gas, Landfill gas, Coal, Solar PV)	• Eastern Water Reclamation Facility (EWRF) • Water Conserv II Water Reclamation Facility (WCII WRF)	• Orange County Landfill • Compost Production
Case 3	*Increase in renewable energy (solar)*	• Area of 5000 m^2	• Curtis H. Stanton Energy Center (e.g., Natural gas, Landfill gas, Coal, Solar PV) • Inclusion of additional solar PV farm near Conserv II	• Eastern Water Reclamation Facility (EWRF) • Water Conserv II Water Reclamation Facility (WCII WRF)	• Orange County Landfill • Compost Production
Case 4	*Climate change impact + inclusion of stormwater reuse*	• Area of 5000 m^2	• Curtis H. Stanton Energy Center (e.g., Natural gas, Landfill gas, Coal, Solar PV) • Inclusion of additional solar PV farm near Conserv II	• Eastern Water Reclamation Facility (EWRF) • Water Conserv II Water Reclamation Facility (WCII WRF) • Stormwater reuse/recycle (e.g., storage tanks) area of 40,000 m^2 or volume of $1.60(10)^8$ L	• Orange County Landfill • Compost Production

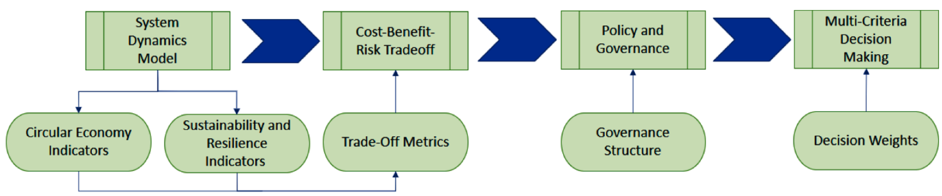

Fig. 3. Flowchart of methodology components in this study.

relevant data are summarized in Table S6-S10. The interactions between the five key entities in the nexus from which the associated material and energy flows are visualized in Fig. 4. The proposed life cycle is a 12-month period in which a monthly time scale is applied in the SDM.

The input variables employed in the SDM were obtained from real-world data or conservative assumptions. According to the USEPA (2018), yard trimmings contain 12.1% of the total municipal solid waste generated. Therefore, it was assumed that 90% of urban farm food waste is composted (denoted as compost 1 or food waste compost hereafter), and 10% of the total municipal solid waste received by OCL is yard waste used in the production of compost (denoted as compost 2 or landfill compost hereafter). A 30% food waste produced from the total urban food production was assumed based on the estimate of 30–40% food wasted from the total food supply in the US (USDA, 2020). Further, the

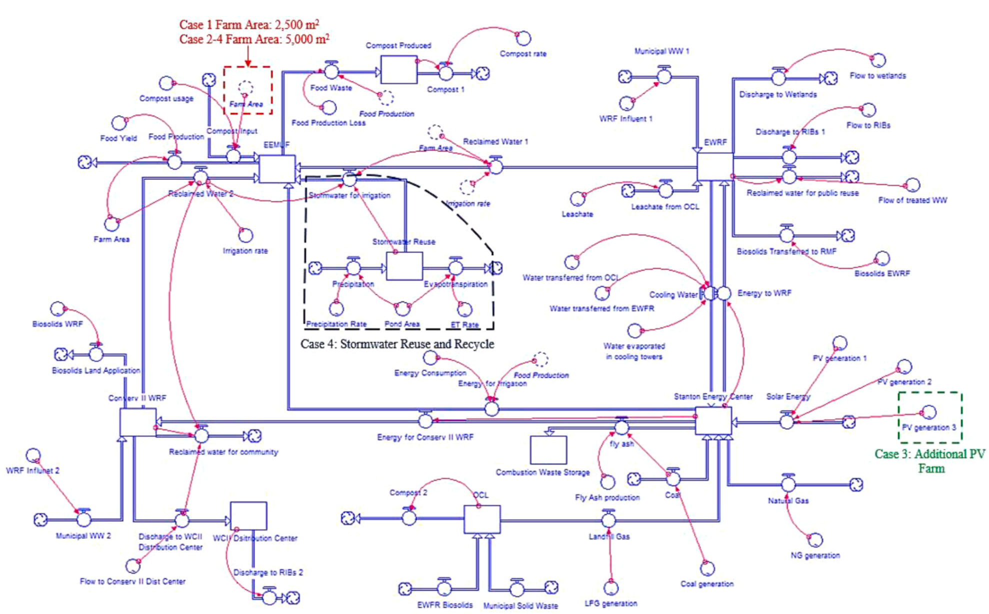

Fig. 4. System Dynamics Model for a) Case 1 (base), Case 2 (expansion of urban agriculture-red box), Case 3 (increase in solar PV farms-green box), and Case 4 (stormwater reuse and recycling-blue box).

required compost needed per agriculture area was determined as 0.95 kg•m^{-2} (8,500 lb•ac^{-1}) based on the typical range of 0.34–2.24 kg•m^{-2} (3000–20,000 tonne•ac^{-1}) of annual application. A summary of all the input variables employed in the SDM for the different agents is included in Supplementary Information Tables S3-S7.

3.2. Circular economy indicators

The performance of a circular economy can be measured using various indicators that influence economic development: societal behavior, sustainable resource management, and business operations (Lieder and Rashid, 2016). Societal behavior reflects actions by the community towards a circular economy that includes willingness for recycling/remanufacturing, reuse, and change in consumption attitude towards the disposition of paying more for durability and sharing. Sustainable resource management encompasses several indicators that assess resource demands, decrease in environmental impact, and increase in resource security. Business operations relates to the business models modified for transitioning to a circular economy by following the principle of circularity and a closed-loop system. Further, a total of 10 indicators corresponding to the areas of production and consumption (e.g., food waste, self-sufficiency of raw materials), waste management (e.g., recycling rates), secondary raw materials (e.g., use of recycled materials to replace raw materials), and competitiveness and innovation (e.g., investments for innovations) are used by the European Commission to address circular economy (European Commission, 2021).

In this study, the circular indicators used for system analysis include the evaluation of material and energy efficiency within the nexus, consumption of raw materials versus secondary materials (byproducts), analysis of value from waste, and value from food production. Hence, in each scenario of the case study, the primary evaluation of the circular economy of interest includes: 1) reduction in raw material consumption (e.g., reclaimed water utilization as a substitute for potable water), 2) recycle and reuse (e.g., food waste reuse), 3) production from secondary material (energy from landfill gas), and 4) services (urban food production in the community), as described by Table 2.

3.3. Sustainability and resilience indicators

Food, energy, and water indices related to sustainability and resilience help give further insight into the SDM results of the FEWW nexus. In this study, the term resilience describes the irrigation water supply resilience in the water sector corresponding specifically to the reclaimed water infrastructure. In this system, the water resilience index (WRI) is formulated as the ratio between the irrigation water supply demanded by the EEMUF and the total reclaimed water supplied by the water sources, including reclaimed water from EWRF and WCII and stormwater (Eq. (1)).

$$WRI = \frac{I_{EEMUF}}{\sum RW_{irrigation}} \tag{1}$$

where WRI is the water resilience index, I_{EEMUF} is the irrigation water supply required for EEMUF, and $RW_{irrigation}$ is the total reclaimed water supplied by EWFR and WCII for irrigation. In this context, food resilience is quantified as a food security index (FSI) for the Orlando population of 287,000 individuals. The food security index is an indicator of whether the urban agriculture system can support the community food consumption with respect to the produce (vegetables harvest), understanding that a healthy human diet encompasses various food staples. Utilizing the 2003 World Health Organization's guideline recommendation of daily food intake of 4 kg per day per person, the FSI can be calculated from the total urban food production (vegetable) in the FEW nexus (Eq. (2)). However, this index is limited to addressing vegetable crops and does not consider other staples in human nutrition, which may not reflect the required daily nutritional value.

$$FSI = \frac{F_{produced}}{F_{intake}} \tag{2}$$

where FSI is the food security index (food consumption ratio), $F_{produced}$ is the total food produced by EEMUF, and F_{intake} is the daily recommended food intake for an adult (4 kg). A value closer to 0 is preferred for WRI, whereas a value greater than 1 is preferred for FSI to demonstrate greater reliability. Although energy resilience can also be explored, evaluating energy sustainability is more appropriate since a more in-depth analysis of energy in the nexus is necessary. Furthermore, the environmental sustainability of the FEW nexus, like its carbon and water footprints, can be evaluated via SDM by employing combustion emission and water consumption factors for the four energy generation fuels to determine greenhouse gas emissions (GHG) and water utilization related to electricity production. Since CSEC is fuel diverse, the contribution of each individual fuel source towards the energy demand for irrigation was considered. Recognizing the energy production of coal, natural gas, landfill gas, and solar power in CSEC, it was determined that coal and natural gas each account for 48.3% of energy production, followed by landfill gas with 2.4% and solar with 1%. The combustion emission factors utilized for bituminous coal, natural gas, landfill gas, and solar power, were 93.28 kg $CO_{2\text{-eq}}$ $MMBTU^{-1}$ (318.36 kg $CO_{2\text{-eq}}$ MWh^{-1}), 53.06 kg $CO_{2\text{-eq}}$ $MMBTU^{-1}$(181.09 kg $CO_{2\text{-eq}}$ MWh^{-1}), 52.07 kg $CO_{2\text{-eq}}$ $MMBTU^{-1}$ (177.71 kg $CO_{2\text{-eq}}$ MWh^{-1}), (EPA, 2014), and 40 kg $CO_{2\text{-eq}}$

Table 2
Indicators Used for Assessing Circular Economy in This Study.

Indicators	Assessment	Formula	Variables
Reclaimed water utilization	Quantity of avoided potable water demand from reclaimed water use in a community	$RW_{irrigation} = \sum IR_{crop} * A * t$	$RW_{irrigation}$=reclaimed water for irrigation (L•d^{-1}) IR_{crop}= irrigation rate representing water necessary for crop cultivation (L•m^{-2}•d^{-1}) A= area of urban agriculture system (m^2) t= time (day)
Food waste reuse	How much food waste is transformed into compost in a community	$FWR = \frac{F_{waste}}{C}$	FWR= food-compost ratio F_{waste}= food waste (kg•$month^{-1}$) C= compost (kg•$month^{-1}$)
Waste to energy generation	The ratio of waste produced to landfill gas generated in a community	$WTE = \frac{M_{waste} * E_{LFG} * conversion \left(\frac{1\ ton}{907.2\ kg}\right) * 24\ h * 30d}{LFG}$	WTE= waste to energy ratio M_{waste}= Municipal waste (kg•$month^{-1}$) E_{LFG}= energy produced per $1(10)^6$ tons of landfill waste (MW• mill ton^{-1})* LFG= landfill gas (MWh•$month^{-1}$)
Food production	Local food production available for a community	$F_{production} = \sum F_{yield} * A$	$F_{production}$= food produced (kg•$month^{-1}$) A= area of urban agriculture system (m^2) F_{yield}= food yield of crops (kg•m^{-2}•$month^{-1}$)

* 0.78 MW• million US ton^{-1}(EESI, 2013).

MWh^{-1}(Koffi et al., 2017), respectively. The water consumption factors for bituminous coal, natural gas, landfill gas, and solar power were 2.62 $(10)^3$ L•MWh^{-1} (692 gal•MWh^{-1}), 650.16 L•MWh^{-1} (172 gal•MWh^{-1}), 0 L•MWh^{-1} (0 gal•MWh^{-1}), 7.56 L•MWh^{-1} (2 gal•MWh^{-1}), respectively (Wilson et al., 2012). The carbon emission and water consumption factors for crop production associated with agriculture land use were also considered in the determination of the carbon and water footprints. The carbon emission and water consumption factors associated are delineated in Table S3 and S4. As the possible types of crops cultivated across the EEMUF are numerous (Table S2), three crops with highest yield per area (i.e., cabbage, tomato, and carrot) were selected for investigation. To further address another sector of the FEWW nexus, the energy sustainability index (ESI) was evaluated as an indicator of local energy resilience (Eq.3). The ESI is used to measure sustainable development given the increase in renewable energy sources for energy supply in Orlando (a value closer to 1 is preferred). Considering the residential, commercial, and industrial electricity consumption of 1.8 $(10)^3$ kWh•$month^{-1}$, 6.09$(10)^3$ kWh•$month^{-1}$, and 78.6$(10)^3$ kWh•$month^{-1}$ (Electricity Local, 2021), respectively, the total energy consumption can be estimated. Here $E_{produced}$ is the energy produced from the CSEC and Solar PV farm, and $E_{consumed}$ is the energy consumed in Orlando (e.g., residential, commercial, and industrial).

$$ESI = \frac{E_{produced}}{E_{consumed}} \quad (3)$$

3.4. Decision-Making evaluation

3.4.1. Cost-Benefit-Risk tradeoff

Exploring cost-benefit-risk tradeoffs between the different FEWW sectors and the corresponding technologies aids in decision-making evaluations for each proposed scenario. Given public-private partnerships, this merits an investigation that can have conflicting views on decision-making and risk assessment strategies. Yet, the primary goal for any stakeholder is to minimize cost through cost-effectiveness, minimizing risks, and maximizing benefits, which can be realized through the evaluation of cost-benefit-risk tradeoffs. Therefore, evaluating tradeoffs in terms of food security, energy resilience, and water sustainability is essential. For example, resilience and sustainability address vulnerabilities in the critical infrastructure system that can surface due to environmental changes, like climate change impacts. The cost-benefit-risks tradeoffs associated with the four sectors are described in Table 3.

Table 3
Cost-Benefit-Risk Tradeoffs for an Urban FEWW Nexus System.

FEWW Sector	Cost	Benefit	Risk
Food: *Urban Agriculture*	•Water and energy costs for irrigation •Fertilizer and compost cost •Continuous maintenance and monitoring	•Increased crop yield if combined with agriculture technologies (e.g., drip irrigation, sensor monitoring) •Food resilience and controllable food supply •Provides access to low access communities (food desert) •Help in water and air quality control •Promote social health (e.g., community gardens) •Bring economic benefits from food supplied to nearby markets	•Production may be affected and damaged by the extreme weather and animals •Non-native crops can be more vulnerable and need more care
Energy: *Coal*	•High capital and O&M costs •Water dependent for cooling the towers of the coal-fired plant •Air pollution control and treatment •Water treatment from water used in pollution control	•Affordable energy source •Established energy generation technology and process •Low extraction costs	•Potential for air pollution and GHG emissions •Acid rain •Extraction can contaminate water sources and environments •Large land use, deforestation, and erosion •Resources depletion •Waste generation
Energy: *Natural Gas*	•Requires collection and storage units •High cost of infrastructure (pipelines)	•Less emission of GHG in comparison to coal •Less electricity cost compared to coal	•Extraction can contaminate water sources from hydraulic fracturing •Highly flammable •Gas leaks
Energy: *Solar PV*	•High installation cost •Energy inverter and storage device	• Low O&M costs •Reduction of GHG and carbon footprint •Transitions into energy resilience • Established technology •Installation and implementation is not restricted	• PV efficiency is region limited •PV material is fragile • Large ecosystem footprint from solar PV farms
Energy: *Landfill Gas*	•Requires collection and storage units	•Reduction of GHG and carbon footprint •Recycling and reutilization of organic materials and waste • Byproduct of natural organic decomposition •Methane burns more efficiently than coal • Low O&M costs	•Production depends on the type of waste and decomposition process in the landfill
Water: *Reclaimed Water*	• High capital and O&M costs •Treatment processes are energy-intensive •Distribution system	•Promoted water reuse •Quality control from regulations for public use •Reduction in potable water dependence •Alternative source of irrigation water compared to surface and groundwater sources •Water resilience and sustainability	•Distribution and use can be restricted by regulations
Water: *Stormwater reuse (wet retention ponds)*	•Initial capital cost	•Low or minimal capital and operation cost •Stormwater quantity and quality control •Reduction in potable water dependence •Alternative source of irrigation water compared to surface and groundwater sources •Groundwater and aquifer recharge	•Transport of pollutants and sediment from stormwater runoff • May need a large area for subsurface storage
Waste: *Landfill (compost)*	• Transportation of compost	• Low O&M costs •Reduction of GHG and carbon footprint •Decreases waste and reduces landfill area needed •Useful for food waste from agriculture utilization •Reduces dependence on fertilizers • Stored and treated in a controlled environment	

Although open field farming is expected in many suburban agriculture systems, implementing urban farming technologies and methods such as drip irrigation and soil sensors can help minimize resource utilization and maximize crop yield and food resilience. The implementation of renewable energy sources like solar PV and landfill gas and the replacement of traditional nonrenewable fuel sources like coal, natural gas, and oil in energy generation can aid in the reduction of GHG and carbon emissions by transitioning toward more sustainable energy generation. Moreover, energy resilience is achieved by reducing dependence on traditional utility power energy fuel sources. Water resilience and sustainability are promoted through the utilization of reclaimed water from wastewater treatment facilities, in addition to the use of stormwater.

3.4.2. Multi-Criteria decision making

Multicriteria decision-making analysis is a support tool based on possible cost-benefit-risk tradeoffs in a decision-making arena. Evaluating the benefits from the aforementioned four FEWW nexus sectors, including food security, energy sustainability, and water resilience, can be used as variables that influence the criteria of interest. For example, the cost-benefit tradeoffs of the four cases presented in the case study can be compared and analyzed with the technique for order preference by similarity to the ideal solution (TOPSIS) approach Hwang and Yoon, 1981). TOPSIS is hence used as a multicriteria decision tool for decision-making analysis that allows the determination of positive (S_i^+) and negative (S_i^-) Euclidian distances (Eq. (7)), where the performance score (P_i) (Eq. (7)) helps determine the most ideal solution. First, the vector normalization (Eq. (4)) is performed, followed by the calculation of positive and negative ideal solutions (Eq. (5)) and Euclidian distances (Eqs. (6) and ((7)). In this study, the ideal solution is represented by scenarios in the four cases (Cases 1, 2, 3, and 4); the criteria include carbon footprint, water footprint, WRI, FSI, ESI, $RW_{irrigation}$, FWR, WTE, food production (kg), and stormwater reuse (0 = no use, 1 = use).

$$r_{ij} = \frac{X_{ij}}{\sqrt{\sum_{j=1}^{n} X_{ij}^2}} \tag{4}$$

$$A^+ = \left\{ v_1^+, \dots, v_j^+ \right\} \tag{5}$$

$$S_i^+ = \left[\sum_{j=1}^{n} \left(v_{ij} - v_j^+ \right)^2 \right]^{\frac{1}{2}} \tag{6}$$

$$S_i^- = \left[\sum_{j=1}^{n} \left(v_{ij} - v_j^- \right)^2 \right]^{\frac{1}{2}} \tag{7}$$

$$P_i = \frac{S_i^-}{S_i^+ + S_i^-} \tag{8}$$

Here r_{ij} is the normalized score of Case $i = 1,2,3,4$, X_{ij} is the score of Case i and criterion $j = 1,..,10$, $v_{ij}$is the weighted normalized vector for Case i and criterion j, where $v_{ij} = w_j r_{ij}$and $w_j$is the assigned importance of weight for criterion j, meaning that the importance assigned to each criterion depends on the priority or significance; $v_j^+$is the ideal best value based on v_{ij}, and $v_j^-$is the ideal worst value based on v_{ij}, A^+, A^- is the positive and negative ideal solution, S_i^+, S_i^- is the positive and negative distance between Case i and the overall score for Case i, and P_i is the performance score of Case i or its relative closeness to the ideal solution. The significance of the weights for the criterion was assigned in a similar range (0.0985–0.101) since typically, w_j values tend to range between 0 and 1, where more emphasis was given to the WRI, FSI, ESI, $RW_{irrigation}$, food production, and stormwater reuse, as these indicators help visualize the impact of FEWW nexus on sustainability and resilience.

3.5. Policy and governance in a FEWW nexus

Posing further challenges and complications in the decision-making process, factors like policy and governance impact the planning, design, and operation of any nexus. This is because regulations and standards are enacted to safeguard and aid the community's interests with respect to risks, contaminants, and the provision of programs that provide financial assistance to promote technology implementations. For instance, water and air pollution treatment and control regulations affect the process of water treatment, wastewater treatment, and even power generation. Further difficulty is presented due to the coexistence of public and private entities; however, this also offers possibilities for partnerships between the two, which can benefit policy implementation. Yet, the fragmentation arising in the food, energy, water, and waste policies causes difficulties in providing coherence in governance and policymaking. Implementing a FEWW nexus in a community can aid in exploring the feedback between resource productivity and policy decision-making in the food, energy, water, and waste sectors between public and private entities. Therefore, it is possible to enhance policy-making for sustainable development and, conversely, identify stresses or pressures from policy affecting both private and public entities. Policy instruments are used in combination with environmental regulation and standards and the economy to incentivize policy implementation and enforcement. Policy instruments encompass four categories: economic and financial instruments, legal and regulatory instruments, social and cultural instruments, rights-based instruments, and customary norms (Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services). Economic and financial instruments help change behavior and promote policy implementations via the utilization of taxes, subsidies, and tradable pollution permits. Hence, the interaction between policy and governance impacts both the public and private sectors and, in turn, impacts decision-making and risk assessment.

In Florida, the following incentives for renewable energy applicable for employment include the Federal Solar Investment Tax Credit (ITC), Solar System Property Tax Exemption, and Home Solar System Sales Tax Exemption. The ITC was enacted in 2006 to promote renewable energy, specifically solar energy, providing a 26% tax credit for residential and commercial solar systems up to 2022, dropping to 22% in 2023 and 10% thereafter (U.S. Department of Energy, 2021). The Florida solar rebates and tax credit programs extend the ITC policy mechanism to promote solar energy further. The Solar System Property Tax Exemption provides a property tax exemption on the additional home value from the solar system (SEIA, 2021), while the Home Solar System Sales Tax Exemption gives a tax exemption for solar system installation, constituting 6% tax for a residential solar system. The Orlando Utilities Commission-Residential Energy Efficiency Rebate Program offers rebates to customers with residential energy-efficient improvements regarding heat pumps, building insulation, high-performance windows, window films, and duct repair. In the water sector, environmental credit trading, such as Water Quality Trading, permits a party with high pollution reduction costs to compensate another party that has less costly pollution reduction (Boyd, 2004). For reclaimed water utilization, the treatment criteria follow regulations and statutes from the Florida Administrative Code Chapter 62–610, F.A.C. and Chapter 62–555, F.A.C. The quality standards require the reclaimed water to meet minimum and secondary treatment with a high level of disinfection (62–610.460, F.A.C). Reclaimed water with land application purposes cannot surpass 12 mg•L^{-1} of nitrogen or have less than 10 mg•L^{-1} total suspended solid before discharge to the application/distribution system (62–610.510, F.A.C). Similarly, the Florida Pollutant Tax enforces a tax on pollutant production under the categories of non-petroleum-based products, petroleum-based products, and perchloroethylene (Florida Department of Revenue). The implementation of water procurement taxes in Florida aims to reduce environmental impacts on Florida's spring water supply by taxing public water systems water extraction at a rate of \$0.033 L^{-1} (\$0.125 gallon^{-1}). This revenue is utilized in the

Wastewater Treatment and Stormwater Management Revolving Loan Trust Fund for funding water and wastewater treatments. Florida Farm Subsidies are also provided for agriculture in areas related to sugar, cotton, peanut, livestock, corn, dairy, and trees. Each of the subsidies specific to crops include price loss coverage, market assistance, quota buyout, and agricultural risk coverage. Additionally, the environmental quality incentives program provided by the Natural Resources Conservation Service of the USDA provides financial assistance to agricultural producers to preserve surface water and groundwater sources, improve air and water quality, and reduce soil erosion. Further assistance is offered to historically underserved participants to advance the EQIP to help in costs related to material acquisition and contracting (NRCS, 2021).

4. Results

4.1. System dynamics modeling

The results from the SDM analysis for the four cases empower the understanding with respect to the different sectoral roles in an urban FEWW nexus in Orlando (Table S11-S14). The different sectoral role is tied to a) food, energy, water, and waste flows (Fig. 5), and b) explored interrelatedness that provides insight regarding the impact of each on the system. In Fig. 5, the flows and relations include reclaimed water used for irrigation in the EEMUF for food production, fuel types (e.g., solar, natural gas, etc.) used by the CSEC for energy generation, reclaimed water provided for cooling towers of the CSEC, and OCL yard waste used for compost production. The blue color represents flows to CSEC for energy production. The orange color represents reclaimed water flow used for energy generation, and the dark green color signifies reclaimed and irrigation water supplied for food production, the light green color represents landfill compost, and the purple color represents the waste flow for compost byproducts. Although Cases 1, 2, and 3 may have the same food, energy, water, and waste components, there are distinctions with regard to changes in urban agriculture or renewable energy production according to the specific case. The structure of the interconnections visualized in Fig. 5 (a, b, c) is similar; however, there are differences in the annual amount of food production, food waste, food waste compost, and solar energy. A distinction is noted in the food production, as it increases from Case 1 ($1.06(10)^5$ kg) to Case 2 ($2.12(10)^5$ kg) (Fig. 5(a) and 5(b)), whereas it remains unchanged for Case 3 and Case 4. Similarly, both food waste and food waste compost increase from $3.17(10)^4$ kg and $3.49(10)^4$ kg to $6.35(10)^4$ kg and $5.71(10)^4$ kg, respectively, in Cases 1 and 2, and remains the same for the rest of cases. An increase in solar energy generation from $1.76(10)^6$ MWh to $2.65(10)^6$ MWh starting in Case 3 and continuing for Case 4 is noted in Fig. 5 (c). Case 4 is described by Fig. 5(d), wherein it incorporates stormwater as an additional irrigation source. Here the stormwater provides an additional $1.16(10)^8$ L of irrigation water to the EEMUF, while the food, energy, and waste flows are unchanged compared to those in Case 3.

4.2. Urban agriculture

The SDM results for Case 1 show a food production of 105.8 tonne•year^{-1}, compost utilization of 0.198 tonne•year^{-1}, and food waste generation of 31.7 tonne•year^{-1}. The compost produced by the food waste accumulated in the EEMUF is 28.53 tonne•year^{-1}. A similar relation is observed for Case 2, where the available area specified for urban agriculture is increased, and the food production, compost utilization, food waste generation, and food waste compost production are 211.60 tonne•year^{-1}, 0.397 tonne•year^{-1}, 63.48 tonne•year^{-1}, and 57.07 tonne•year^{-1}, respectively. Since the values for urban agriculture do not change for Case 3 and Case 4, these variables remain the same.

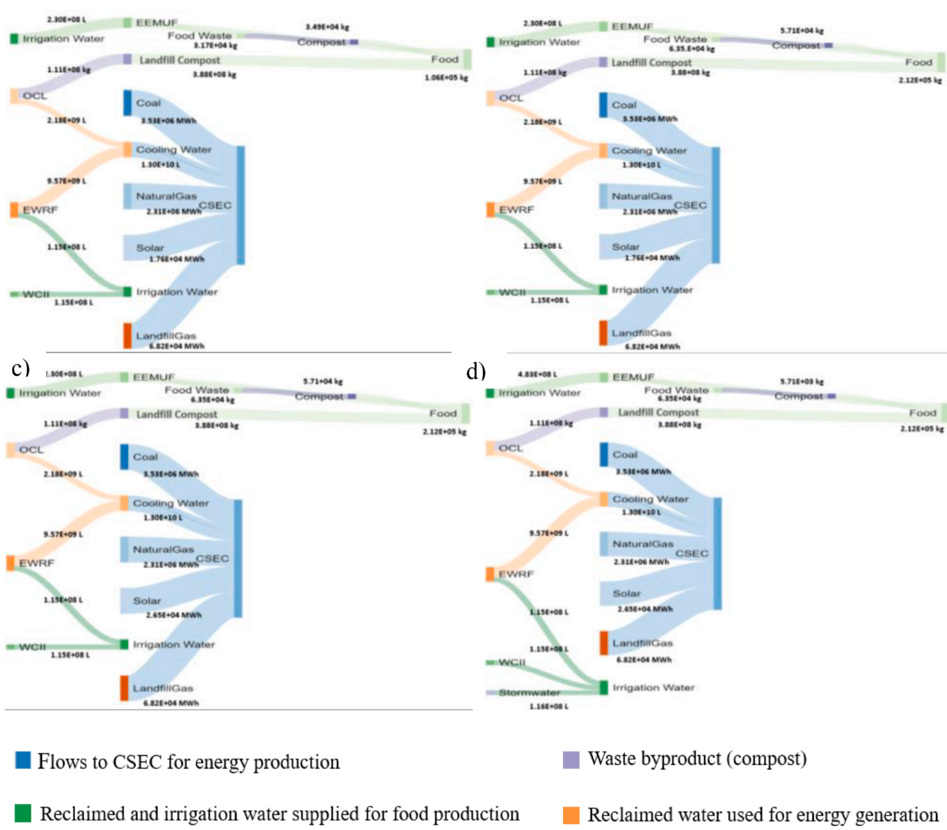

Fig. 5. Sankey diagram of fundamental framework flows in a FEWW nexus (a) Case 1, (b) Case 2, (c) Case 3, and (d) Case 4.

4.3. Energy generation

According to the CSEC energy database, the monthly energy generated from the two solar PV farms operated by the CSEC, based on 2019 energy data, was determined to be $1.47(10)^3$ MWh. In Case 1, when considering the monthly average electricity demand of providing irrigation to the urban farms of 0.67 MWh, with an annual demand of 7.37 MWh, it is noted that the energy generated from the solar power is sufficient to cover the urban farm system demand independently given that the energy generated from the two solar power plants is $1.47(10)^3$ MWh per month or $1.76(10)^4$ MWh per year. However, it is noted that the annual energy produced from the landfill gas ($6.82(10)^4$ MWh) is higher than the energy from the PV farms ($1.76(10)^4$ MWh); this demonstrates the impact of the integration of OCL in the FEWW nexus, as it provides a fuel source to the CSEC for energy generation. Yet, the primary fuel source for energy generation in CSEC remains as bituminous coal ($3.53(10)^6$ MWh), followed by natural gas ($2.31(10)^6$ MWh). In Case 2, where the urban farming sites are expanded, the energy demand for irrigation increases to 1.34 MWh per month and 14.74 MWh annually. This relation remains the same for Cases 3 and 4, where the area for urban agriculture is maintained as 5000 m^2. Similarly, the coal, natural gas, and landfill gas energy generation remain constant for Cases 3 and 4; however, the annual solar energy generation increases in Case 3 to $2.65(10)^4$ MWh due to the additional PV farm. This solar energy generation is maintained in Case 4. Additionally, the total annual cooling water supplied to the CSEC is $1.30(10)^{10}$ L; this considers the water obtained from EWRF and OCL ($2.89(10)^9$ L), and the water lost in the evaporation process in the cooling towers,

4.4. Reclaimed wastewater management

According to the irrigation rate for crop cultivation based on the selected categories of crops maintained in the EEMUF, the reclaimed water necessary for irrigation is $9.60(10)^6$ L•month^{-1} for an area of 2,500 m^2 (Case 1). For Case 1, the quantity of treated reclaimed water available for public use by the EWRF and the WCII is a monthly average of $1.71(10)^9$ L and $8.46(10)^8$ L, respectively, which is sufficient to provide the reclaimed water to the EEMUF for irrigation and still have effluent to provide for community use and discharge to RIBs. If 9.60 $(10)^6$ L•month^{-1}is proposed for allocation by each water reclamation facility, the EWRF would discharge an average of $1.56(10)^7$ L to the RIBs for groundwater recharge, $1.71(10)^9$ L for community reuse, and 9.57 $(10)^9$ L to CSEC for the cooling towers. Similarly, the WCII can provide an average of $1.07(10)^9$ L to the RIBs for groundwater recharge, 8.46 $(10)^8$ L for community reuse, and $1.20(10)^9$ L to the WCII Distribution Center in Case 1. For Case 2, due to the expansion of urban agriculture, the irrigation water demand increases to $1.92(10)^7$ L•month^{-1}. Although the discharge of EWRF to the RIBs and EWRF distribution to CSEC remain unchanged, the reclaimed water for community reuse reduces slightly from $1.71(10)^9$ L to $1.70(10)^9$ L. The discharge to the RIBs and the WCII distribution center remains the same for WCII, with only a slight decrease in the quantity of reclaimed water for community reuse from $8.46(10)^8$ to $8.37(10)^8$ L is observed. These observations are also noted for Case 3 and Case 4 because the expansion of the urban agriculture system is consistent across Cases 2–4. The decrease in the available reclaimed water for community reuse can be attributed to the increase in irrigation water demand by the EEMUF. The annual quantity of treated reclaimed water distribution by the EWRF and WCII facilities is depicted in Fig. 6, with a distinction between the different reclaimed water uses.

4.5. Solid waste

There are various components and flows in the waste sector, including food waste, biogas generation, compost production, leachate generation, and biosolids from wastewater treatment. The waste accumulated in the landfill cells belonging to municipal waste, including yard waste, can generate landfill gas, used for energy generation by the CSEC. The compost resultant from the components of yard waste of the municipal solid waste transported to the OCL was determined as 3.88 $(10)^8$ tonne•$y^{-1}$for all four cases. Further, the OCL facility produced an average of $3.14(10)^8$ L of leachate monthly and $3.77(10)^9$ L annually, which is transported to the EWRF for treatment. Since the OCL produces sufficient landfill compost to supply the community, the EEMUF can also

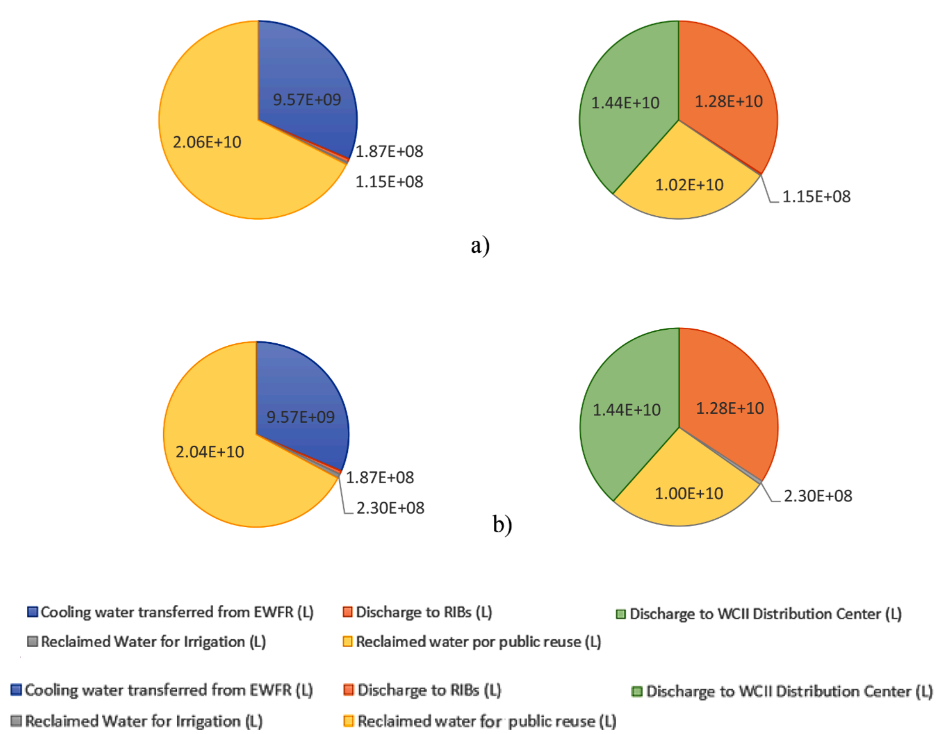

Fig. 6. Annual Distribution of Reclaimed Water from EWRF (Left Panel) and WCII (Right Panel) in a) Case 1, and b) Case 2,3,4.

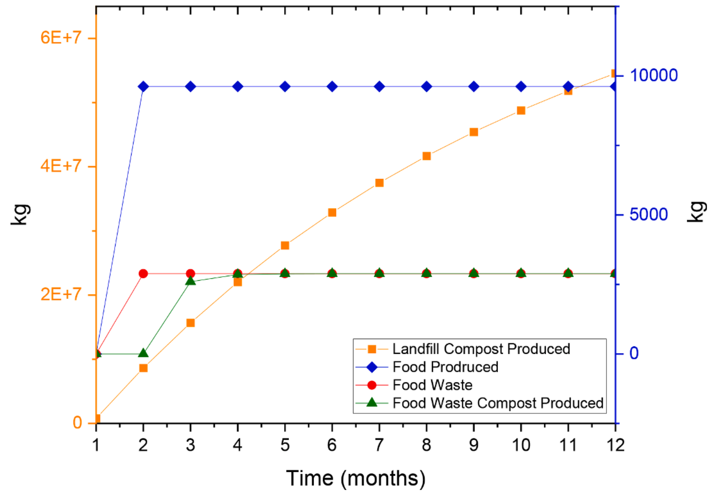

Fig. 7. The overall relationship between urban food production, food waste compost production, and landfill compost use in all cases (**left axis**: Landfill Compost Produced; **right axis**: Food, Food Waste, and Food Waste Compost Produced).

utilize this resource (landfill compost) for urban farming in congruence with the food waste compost. Further, the Class A biosolids generated by EWRF sludge for land application were determined as 117.25 tonne•y^{-1} for all four cases. Currently, these biosolids are land applied at specific locations by the facility and not for public use. The general relation and trend of the annual food production, landfill compost, and food waste compost use are shown in Fig. 7, which depicts the correlation between the three.

4.6. Circular economy analysis

The effect of the FEWW nexus on the circular economy can be explored using sustainability indicators. Primarily, the services and resource management of the FEWW nexus in the four sectors can be assessed in a community-scale circular economy (Orlando, FL) based on Table 2. This includes food production, reclaimed water for irrigation, renewable energy sources (e.g., solar and landfill gas), and stormwater reuse. The surface water and potable water utilization avoided from treated reclaimed water are measured as the total water used by EEMUF for crop irrigation ($RW_{irrigation}$). Thus, the avoided demand on potable waste or the reduction of raw material consumption is proportional to the reclaimed water allocated for irrigation of $1.15(10)^8$ L•y^{-1} for Case 1, and $2.30(10)^8$ L•y^{-1} for Cases 2, 3, and 4. Furthermore, the demand for potable water can also be avoided with stormwater reuse, as in Case 4, where $1.16(10)^8$ L•y^{-1} is available.

Table 4
Summary of Sustainability and Resilience Indicators in This Study.

Scenario	Carbon Footprint (kg $CO_{2\text{-eq}}$)	Water Footprint (L)	Water Resilience Index (WRI)	Food Supply Index (FSI)	Energy Sustainability Index (ESI)
Case 1	$1.31(10)^6$	$1.51(10)^7$	0.50	0.09	0.809
Case 2	$2.63(10)^6$	$3.03(10)^7$	0.50	0.18	0.809
Case 3	$2.63(10)^6$	$3.03(10)^7$	0.50	0.18	0.810
Case 4	$2.63(10)^6$	$3.03(10)^7$	0.48	0.18	0.810

4.7. Sustainability and resilience

The environmental indicators are the carbon footprint expressed as greenhouse gas emission (kg $CO_{2\text{-eq}}$) and water footprint (L) shown in Table 4. These indicators were implemented in the SDM analysis by utilizing emission and water use factors. Fig. 8 shows the SDM for this carbon and water footprint analysis in the proposed life cycle (one year). The carbon and water footprints increased from Cases 1 to Case 2 onwards; this is a response to the increase in the urban farming land use starting from Case 2–4. It appears that the use of solar energy resultant from the addition of another solar PV farm by the CSEC in Cases 3 and 4, does not greatly impact the carbon and water footprints as these remain constant from Case 2 to Case 4. Similarly, the increase in the water footprint is due to the increase in reclaimed water utilization by EEMUF for food production to accommodate the increase in land and crop cultivation. The WRI remained stable at 0.50 for Cases 1, 2, and 3 and only decreased slightly to 0.48 in Case 4. This demonstrates the impact of stormwater reuse as an additional source of irrigation water for urban agriculture. Stormwater reuse transitioned the WRI closer to its desired value, as a value close to 0 is preferred. Yet, increasing the quantity of irrigation water supply by the WRFs (water reclamation facilities) would increase water reliability. On the contrary, the food supply index (FSI), corresponding to food resilience, increased from 0.09 in Case 1 to 0.18 in

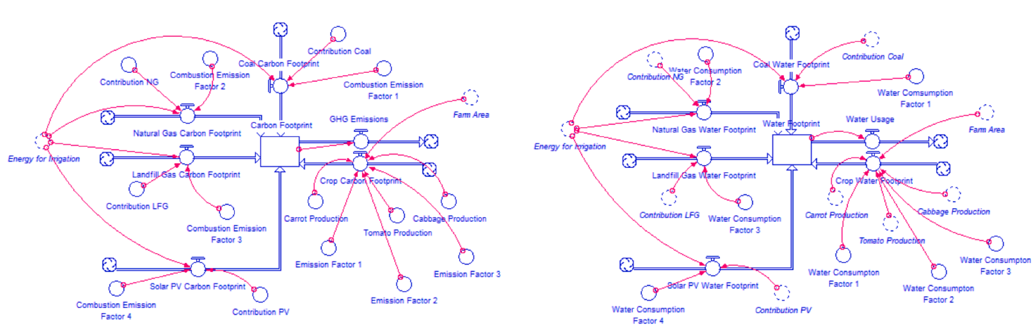

Fig. 8. Carbon Footprint (Left Panel) and Water Footprint SDM (Right Panel).

Cases 2, 3, and 4. This increase is preferred, as it suggests more food availability from production in comparison to consumption and results from the incrementation of the urban agricultural area that was implemented beginning in Case 2. Since the energy sustainability index (ESI) increased slightly from Case 1 and Case 2 to Case 3 and Case 4, these differences demonstrate the possible influence of additional solar energy generation used by CSEC.

5. Discussion

5.1. Synergies and interactions in urban FEWW nexus

The synergies and interlinkages in the FEWW nexus provide insight regarding the factors that are impacted in changing conditions. The visualization in SDM illustrates that the urban farming system is the primary sector in the nexus that is influenced and affected by the various interconnections and flows from the energy, water, and waste sectors. That is, the EEMUF does not directly impact facilities in the other FEWW sectors but instead relies on the supply of water, energy, and even landfill compost for operation. In the urban farming system, the food generated by EEMUF represents available fresh food, which can offset the need for purchasing food from external food sources. However, since the EEMUF produces sufficient compost, the EEMUF can transition from purchasing compost from an external company such as Monterey Mushrooms, Inc, and utilize the locally produced compost from the urban agriculture system. If sufficient food compost is made by the EEMUF or acquired from the OCL, stormwater best management practices (BMPs) can be coupled with compost as a form of medium implement for further nutrient abatement for stormwater quality control. The compost BMP technologies that can be contemplated include compost filter socks designed for protection of inlets and stormwater drains, stormwater pollution control, low impact developments (LIDs) (Archuleta and Faucettee, 2011), compost blankets for erosion and stormwater control (USEPA, 2012), and compost filter berm for erosion control (USEPA, 2020).

In the energy sector, the energy demand from the urban agriculture system is supplied by CSEC, which utilized four fuel sources. Yet, when distinguishing the energy generated from the individual fuel types, the EEMUF energy demand can still be supplied solely by landfill gas. Since the generated solar energy is sufficient to maintain the irrigation for the farming sites, the addition of another solar PV farm, as in Cases 3 and 4, will further improve the energy resilience of the nexus and help the CSEC move away from nonrenewable energy sources and decrease its dependence on coal and natural gas. Moreover, an increase in landfill gas generation from the OCL can also enable CSEC to transition into using a more significant percentage of renewable fuel sources, as the monthly and annual energy generated from the landfill gas was observed as $5.69(10)^3$ MWh and $6.82(10)^4$ MWh, respectively.

The synergistic relationship between the food and energy sectors can be further extended to the water sector. The WRFs facilitate the reuse of treated wastewater effluent for different purposes such as irrigation, public reuse, and the use in cooling towers of CSEC. The irrigation water demand in the system is supplied by both WRFs; if there is an interruption of supply from one facility, the other facility can still meet the irrigation demands of EEMUF. However, the employment of the stormwater reuse system in Case 4 serves as an additional layer of reliability in the system with regards to irrigation water supply, as it has the capacity to supply an average of $8.46(10)^6$ L•month^{-1}. With the aid of BMPs, the stormwater reuse system can reduce the stress on the WRFs for irrigation water and free more reclaimed water for public reuse and aquifer recharge via RIBs and the water supply for CSEC, if this demand were to increase.

Since food and water flows are interconnected, the quantification of water and food resilience indices supports the implementation of urban agriculture and reclaimed water. Although the water and food resilience indicators used to quantify resilience for the FEWW nexus may not vary from case to case, the addition of irrigation water supply from the stormwater system to the existing irrigation water supplied by the WRFs in Case 4 lowered the WRI, which is preferred. However, the WRI of 0.50 still suggests water resilience, as the total irrigation water supply is twice the irrigation water required by the EEMUF. The increase in FSI in Case 2 supports the claim of food resilience since there appears to be greater food production than food consumption, according to the assumptions made on the community population and utilizing the recommended daily food intake for an adult. Further, an in-depth analysis of the nutritional value of the harvested food will need to be considered to address adequate nutrition. These findings are crucial if the community wants to be self-sustained in the case of increased resource depletion, which would result in increasing resource competition in the procurement of water and food. However, it should be noted that for the community to be fully self-sustained, further aspects of the food supply have to be considered, provided that the possible crops harvested in the EEMUF are limited. Yet, a disadvantage of having self-sustained and local production without proper redundancies is a lack of protection against disruptions that can interrupt the food supply chain. Currently, the urban agriculture system in place aims to reduce food insecurity. Moreover, the competition between potable water sources can be reduced by implementing reclaimed water and stormwater. Additionally, if reclaimed water demand for RIB and groundwater discharge increases, the stormwater reuse system can be enlarged to support irrigation for urban agriculture. The cost savings from reclaimed water utilization versus public water supply (e.g., potable) can be calculated. Cost-saving can be accomplished by using reclaimed water instead of potable, as the reclaimed water rate schedule includes retail ($0.89 per 1000 gal) and bulk pressure service ($0.69 per 1000 gal) (Orlando, 2021a).

Moreover, the circular economy in the FEWW nexus is tied to the utilization of secondary materials and byproducts influenced by the interconnections in the system, which can be evaluated using factors like food waste reuse (FWR) that represents the relationship between food waste and compost generated by the EEMUF. It is noticeable that the average FWR ratio was 0.91 for all four cases, indicating a linear trend between the food waste produced by the urban farms and the compost generated. This demonstrated an almost closed system in urban agriculture between food waste and compost generation. On the other hand, the average WTE ratio was determined as 0.04, which suggests the level of anticipated landfill gas recovery based on municipal solid waste in this study.

5.2. Interactions of policy, cost-benefit-risk tradeoff, and decision making

Governance structure and function might affect sustainable development as a range of policy instruments may be designed to aid in urban sustainability in the food, energy, and water sectors for sustainability transitions. Investment in innovations and technology development is one of the primary strategies besides economic incentives for promoting and advancing sustainable development. The incentives for renewable and clean energy, such as the ITC, incentivize the expansion of solar energy. The implementation of solar PV is beneficial in areas that receive sizeable solar irradiation, such as Florida, which can take advantage of this resource to produce solar energy. Investment in technologies for stormwater treatment like BMPs and LIDs is also crucial in sustainable development. Stormwater management for reuse is considered, given that stormwater can be viewed as a sustainable resource for mitigating water scarcity due to climate change impact. Policy instruments related to urban farming subsidies are also important in Florida given its involvement in agriculture production, such as the implementation of EQIP, which promotes resource preservation and sustainability through financial assistance to agricultural producers. Support for urban agriculture is also provided, as the benefits related to general urban agriculture practice are substantial and target all three aspects of urban sustainability (social, environmental, and economic). The implementation of alternative sources for irrigation, like reclaimed wastewater and stormwater, also provide various environmental benefits. The high capital and O&M costs related to reclaimed wastewater reuse are unavoidable costs that WRFs incur to ensure adequate pollution control and wastewater treatment. However, a cost-benefit-risk assessment may be necessary to understand the implications before proceeding to implement a policy that promotes technologies and processes that influence the FEWW sectors.

From Table 4, the benefits of utilizing solar PV for energy generation compared to other conventional energy sources are significant, as are the costs and risks of using coal for energy generation. As renewable energy technology continues to evolve, the capital cost of the solar system (integrated with energy storages systems) will continue to drop, which makes the direct cost of renewable energy comparable to, or even cheaper than, energy provided by the regional utilities. In addition, we should note that PV-module-based solar energy systems can be easily installed and operated in a decentralized manner. These decentralized systems can improve the reliability of energy supply, thus avoiding the cost of energy interruption, which can be treated as a large portion of indirect costs that can be avoided by deploying decentralized energy systems. On the other hand, regional power plants usually resort to long-distance transmission and distribution lines to meet the load demand of users, which causes a significant portion of energy loss; however, the utilization of decentralized energy systems can significantly reduce the energy loss due to transmission and distribution since they are generally installed close to the load center. Utilizing distributed renewable energy harvesting methods such as solar photovoltaic can also minimize the investment of building or updating the energy transmission and distribution infrastructures, making it more competitive than merely procuring energy from regional power utilities.

To have more clarity in the planning and design of the infrastructure, the decision-making approach is preferred. Multicriteria decision-making use of TOPSIS can aid in the decision-making and selection process to determine the most appropriate case design in the case study. The alternative solutions represented by the four cases were assessed to determine the most ideal solution according to the closeness of its performance score (P_i) to 1. When considering substantiality and resilience indicators (carbon and water footprints), circular economy indicators (WRI, FSI, ESI, $RW_{irrigation}$, FWR, WTE ratio, stormwater reuse), and urban agriculture food production with specified weights, the most appropriate alternative can be determined, as described by Table 5. The interest in the decision-making selection affects the weights assigned to the different criteria previously mentioned. As such, Case 4, encompassing stormwater reuse in the FEWW system, was selected as the most appropriate alternative for FEWW nexus design, with a tie for Case 3 and Case 2. However, if considering the benefits from increasing renewable energy to reduce the use of nonrenewable energy sources with energy sustainability, Case 3 is suggested as the better option preferred over Case 2.

5.3. Climate change impact

The climate change impact on the urban community can be evaluated according to the stormwater data acquired from the SDM across the four cases. Each case presents progressive change to the base case to visualize a more evolving FEWW nexus during sustainability transitions. For example, the inclusion of stormwater reuse in the nexus in Case 4 can increase the available quantity of treated reclaimed wastewater for community reutilization, which is beneficial if a population increase is expected in the future. The inclusion also adds reliability to the system in case strict regulations for reclaimed wastewater reuse are possibly imposed in the future, hindering the public use of reclaimed wastewater. Currently, in the state of Florida, water management rules ensure the water quality of the reclaimed wastewater is appropriate for land application. Further, the competition for potable water resources can be reduced. If less water is allocated by the WRFs for irrigation and is instead discharged to the RIBs, the aquifers can be recharged to ease the quantity of water pumped for potable water consumption. To curtail environmental impacts with respect to the GHG emissions and reduce the dependency of CSEC on coal and natural gas as primary fuel sources for energy generation, the increase in renewable energy, such as PV farms, can be implemented in addition to landfill gas utilization. In addition, increasing urban agriculture improves community food security and resilience, transitioning the community away from being classified as a food desert and aiding disruptions in the food supply chain during hurricane seasons or extreme weather events. Climate change mitigation can be linked to the diversion of organic waste from landfills, reducing GHG emissions, and providing carbon sequestration from the use of compost and biosolid fertilizer. Despite biosolid fertilizers containing lower percentages of nutrients (e.g., N, P, Ca, S, K, Mg) compared to commercial fertilizers, nutrient percentages of 4.75% total Kjeldahl nitrogen, 0.57% NH_4—N, 4.13% org-N, 2.27% total P, and 0.31% total K were determined (Lu et al., 2012). Hence, the land application of composts and fertilizer resultant from biosolids is an alternative to burning or landfilling, which decreases the GHG to be produced in these processes

Table 5
TOPSIS Multicriteria Decision Making Results.

FEWW nexus solutions	S_i^+	S_i^-	P_i
Case 1	0.112	0.039	0.256
Case 2	0.108	0.049	0.310
Case 3	0.108	0.049	0.310
Case 4	0.039	0.112	0.744

5.4. Limitations and future work

Since various forms of nexus research such as FEW or FEWW nexus implementation have been extensively investigated, there is a need to transition into exploring future innovative aspects for greater sustainability while considering climate change and policy instruments. For instance, we may focus on interdisciplinary solutions of reclaimed wastewater and stormwater treatment that provide co-benefit while also decreasing the community vulnerability due to energy scarcity. This is important to reduce energy consumption and increase efficiency in reclamation facilities as these facilities are one of the major consumption sources of energy in a municipality consuming 30–40% of total energy (EPA, 2017). Finding a technology alternative for the cost-effective treatment of stormwater can facilitate the decrease of reclaimed wastewater utilization. Although rainwater collected directly, unless affected by stormwater runoff from rooftops, is expected to be uncontaminated, stormwater can be treated via electrolysis and fuel cell for hydrogen generation which can be stored in a hydrogen storage system as described by Zhang et al. (2020). However, disadvantages can arise from the use of stormwater (rainwater) harvesting devices in urban agriculture due to maintenance fees to control eutrophication impact (e.g., algae growth) with storage limits.

In this study, only one risk factor (e.g., climate change) was considered in Case 4 to address stormwater availability in the future due to the possible increase in rainfall that may be linked to LIDs to address long-term climate change impact and advance our understanding of adaptive transformations of critical societal infrastructures (such as urban farming). The inclusion of precision farming technologies may help innovate the design, operation, and planning of such infrastructure systems under uncertainties such as climate change and land-use policy with land teleconnection effects. Although policy and governance in the nexus system are discussed to evaluate and understand the implications of the impact via policy instruments on sustainable development, a thorough socioecological analysis specific to the Orlando area can be explored further in the future. Despite the practicality of exploring the cost-benefit-risk tradeoff assessment for the four sectors of the FEWW nexus, the decision-making process is still challenging. The comparison yielded insight primarily regarding the costs and benefits associated with the distinct entities in each sector, where it can be observed that the utilization of solar PV and landfill gas is more economically and environmentally beneficial for energy generation. The benefit of reclaimed wastewater and stormwater utilization is also noted since it provides water resilience and food security from urban farming. Although capital and operation costs are significant for WRFs, it is a co-benefit for wastewater treatment as the effluent can be reutilized for many secondary purposes. Future research can be conducted to acquire more data from each facility in the proposed FEWW nexus to conduct a long-term and well-rounded system analysis that can help answer more challenging research questions.

6. Conclusion

Transitioning toward sustainability is paramount in the present era, specifically in metropolitan regions, given the impact and strain of anthropogenic activities on the environment and resource competition. However, challenges in urban sustainability range from sustainable development problems centered on the interactions and behaviors of distinct stakeholders in association with the social, economic, and environmental aspects. As such, the FEWW nexus approach was applied to incorporate more sectors required for sustainability transitions and achieve a more coherent circular economy, as the traditional FEW nexus is not sufficient to advance the understanding of social, environmental, and economic sustainability simultaneously. While the nexus's planning, design, and operation were related to uncertainties such as climate change impact, synergies embedded in the FEWW nexus can transform the urban farming infrastructure to a broader scope. An SDM portraying the food, energy, water, and waste material flows among different sectors in an urban FEWW nexus was thus developed for system analysis in this paper. The proposed FEWW nexus in Orlando, Florida, provided insight regarding the material and energy flows among the distinct entities in the nexus, demonstrating the co-benefit of utilizing reclaimed water and stormwater for potable water reduction and increasing resource conservation. In addition, composting in the EEMUF and producing biosolid fertilizer and landfill gas provides climate change mitigation to some extent. The utilization of the cost-benefit-risk tradeoff and TOPSIS offered further insight for screening the design alternatives in an urban FEWW nexus leading to favor Case 4 as the most preferable one, given that it included greater renewable energy and stormwater reuse. Such sustainability transitions elucidate the essence of environmental convergence opportunities ad more decision-making with social factors can be taken into account.

Credit author statement

Andrea Valencia carried out data collection, system dynamics modeling analysis, and sustainability transitions assessment; Wei Zhang helped renewable energy assessment with sustainability indexes and essential data; Ni-Bin Chang conceived the conceptual framework of a living laboratory approach for urban sustainability assessment. All three authors jointly wrote the paper.

Declaration of Competing Interest

The authors have no competing interest.

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Supplementary materials

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