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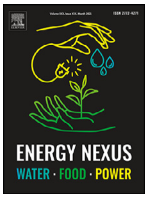

Full Length Article

Water- food- energy- ecosystem nexus model development: Resource scarcity and regional development

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ABSTRACT

Demographic, economic, social, and climate change are all putting pressure increasing on natural resources through global energy, food, and water demand growth, which threatens the well-being of the ecosystems. To address this scientific and political challenge, a dual-purpose optimization tool has been proposed with the approach of minimizing the environmental effects and development costs of the region in line with resource consumption management, which optimally takes resources from the ecosystem, and regarding development approach (eco-tourism development in this study), it has suggested the optimal strategy to improve the economic benefits. Moreover, this model is able to propose some effective management policies on resource planning at the regional level. This approach has been applied to Shif Island in the south of Iran. The main results are: (i) The regional potential has the possibility of increasing more than 2067 tourism numbers per year, which can compensate for a large part of the regional development costs. (ii) The regional management strategy of wastewater and solid waste resources with the view of the nexus approach development of the system (development of the eco-industrial park) and the ecosystem (the relationship between the soil and plant model) and the system development models in line with the regional demand), can reduce waste production to about zero and provide more than 90% of the region's fertilizer needs in order to improve the ecosystem's performance. (iii) In this model, the producers of materials and energy are the main inputs of the ecosystem, and the outputs of the ecosystem include the outputs of the agriculture, forestry, animal husbandry, and fishing process in the remote areas, as well as mineral resources (industrial raw materials and fossil resources), renewable energy, etc. Consumers consist of humans and living organisms of the urban-rural ecosystem.

In general, in this paper, the aim is to develop a practical method for analyzing the symbiosis of living and non-living parts of the ecosystem in terms of water- Food-Energy and Ecosystem nexus model. In this regard, a hybrid technology model has been suggested to minimize the dynamic cost of changes in line to reach an optimal path for the development of living and non-living interaction.

Abbreviation

$AY_{max,i,t}$	maximum yield of crop production
$Area_{ag_{i,t}}$	an area dedicated to the mangrove forest
Biomass $factor_i$	biomass production in kg of crop product
$c_{1,2,3}$	constant coefficients
CP	carbon to phosphorus ratio
CN	carbon to nitrogen ratio
$Crop_{1t}$	tomato production
C_{SOM_t}	carbon concentration in soil (pools)
$Compost_{f_i,t}$	producing compost from composting technology
CT	residual capacity of technology
$CT_{i,t}$	the capacity of technology i
dD/dt	mangrove growth rate
$DEGD_{min}$	minimum degree- day of growth
DEGD	degree- day of growth
emission $factor_{i,t}$	technology diffusion coefficient i
EE	eco-efficiency index
EE^{max}	maximum eco-efficiency
EES	eco-efficiency number
$F_{leaching_N}$	nitrate leaching losses in soil
$F_{P_{immob_t}}$	immobilization of organic phosphorus during mineralization of soil organic matter
$F_{weathering}$	material weathering
g	percentage of residual carbon in the soil after decomposition as SOM
HCT	the historical capacity of technology
$k_{J,1}$ $k_{J,2}$	decay rate constant of soil organic matter (s^{-1})
K_{occl}	phosphorus occlusion rate

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$K_{dep_{pot}}$	sediment reaction coefficient
K	the base reaction rate that forms the enzyme-substrate product complex
m	number of evaluation events
N_{dec_t} and P_{dec_t}	decomposed N and P values
$N_{J,t}$, $P_{J,t}$	pool dimensions (gm−2) of nitrogen and phosphorus
NCT	new capacity of technology
Nr_{N_t}	nitrogen concentration in plant residues
Nr_{P_t}	phosphorus concentration in plant residues
N_{app_t}	applied nitrogen
$N_{C,i}$	the nitrogen concentration of compost
N_{D_t}	nitrogen demand
Ne_{g_t}	the average release of nitrogen gas
RNA	nutrient index (the ratio of phosphate concentration to the maximum phosphate content)
$\boldsymbol{TE_{i,output,t}}$	energy output from technology i
$\mathbf{TE_{i,input,t}}$	input energy to technology i
U_{i_t}	production of tomato biomass
$X_{out,i,t}$	output concentration of various technology combinations i
FWHOUSED	fresh water demand in household
$\mathrm{elec\ factor}_{i,energy,t}$	electricity consumption per mass input to technology i
$EXL_{i,t}$	carbon emissions of each flow
$\mathrm{Fertilizer}_{f_i,t}$	fertilizer consumption in the region
$F_{N_{immob_t}}$, $F_{P_{immob_t}}$	flux immobilization of inorganic Nitrogen and phosphorus in soil
$F_{surf_{P_t}}$	surface adsorption flux of phosphorus
$F_{occl\,p_t}$	phosphorus occlusion flux
$F_{leaching_N}$	nitrate leaching
$F_{weathering}$	material losses due to weathering
$F_{leaching_P}$	phosphorus leaching
$F_{N_{mob_t}}$	gross nitrogen mineralization rate
$F_{P_{mob_t}}$	gross phosphorus mineralization rate
$F_{N_{immob_t}}$	losses of organic nitrogen during the mineralization process
f_{ij}	the fraction of SOM that goes from pool i to pool j
$F_{leaching_P}$	leaching losses of soil phosphorus compounds
F_{dep_N}	deposition of ammonia and nitrate in the atmosphere
F_{surf_P}	depletion of surface phosphorus
F	absorbed nutrient flux
$F_{N_{mob_t}}$, $F_{P_{mob_t}}$	immobilization flux of inorganic nitrogen and phosphorus
F_{surf_P}	adsorption of phosphorus surface flux
$P_{J,t}$, N_{J_t}	total phosphorus and nitrogen added to the soil
$N_{f,i}$	nitrogen produced from manure
Ne_{N_t}, Ne_{P_t}	Erosion of nutrients (Phosphorus and Nitrogen)
Ne_{g_t}	Losses of gaseous Nitrogen
P_{app_t}	applied phosphorus
$P_{C,i}$	phosphorus production from the composting process
Pri	probability of random state variable X in an uncertain system
$P_{C,i}$	phosphorus concentration of compost
$P_{f,i}$	production of phosphorus from manure
P_{dec_t}	decomposition losses of soil organic matter
P_S	adsorbed content for phosphorus
P_{D_t}	phosphorus demand
P_{app_t}	applied phosphorous in the soil
qij	standard value calculated from raw data
qj	sum of the standardized index in year j
S	information entropy of an uncertain system
$\boldsymbol{\alpha_i}$	the upper limit of technology i
ΔS	entropy changes of ecotourism development
$\boldsymbol{\eta_{C,i,t}}$	conversion parameter of different combinations of technology i
$\eta_{i,\ energy,t}$	the energy efficiency of technology i
$\eta_{i,t}$	the efficiency of technology i
$w_i x_i$	environmental impacts
Pr	probability in eco 99 calculation
UWHOUSED	non-drinkable water demand in household

Introduction

Food, Energy, and Water (FEW) are essential resources for a region's sustainable development. These resources have an interconnected effect [46], energy is needed for water pumping, collection, treatment, and distribution of water. At the same time, energy is very important in food production and processing, as in the fertilizers generation, irrigation, packaging, processing, and storage of food, and it appears in the Sustainable Development Goals (SDGs) [44].

Energy provision as one of the sustainable development policies requires regional water resources. The transfer to biofuels will lead to a wider water-food nexus for various sectors, especially global transport in line with the circular economy [20,25]. In 2019, Raul Munoz Castillo et al. analyzed the synergy between land and water use for bioethanol production and its environmental impact across Brazilian states. It showed that there is a significant difference between irrigated and rainfed ethanol production due to water and land scarcity [43]. Next, Mohamad Abdel-Aal in 2020, examined the spatial and temporal effects of the use of anaerobic digestion (AD) as one of the methods of biofuel production, in line with the WEF framework and the quantification of environmental, social, and economic benefits associated. To do this, an agent-based model (ABM) was developed to simulate AD emissions across the UK, and various scenarios were explored to predict the future [1].

Moreover, between food and energy, water is also a vital resource for the sustainable economic and social development of a region. Water security is often a priority in the depletion of triple resources [8] and many scales are selected based on water-based environmental contexts [31,41]. Water resource management in regional development is not just about drinking water production but also includes wastewater management. For the development of an urban-rural area, there is a need to build applicable decision-making tools in terms of resource scarcity consideration, and the minimization of the environmental impact according to the economic power of the area. industrial symbiosis is an approach to optimizing the wastewater treatment system in industrial estates. It is done by reusing organic matter in food wastewater (as an external carbon source in advanced centralized wastewater treatment plants (WWTP). Some biodegradable organic matter, such as food waste, which is abundant in industrial wastewater, can be used as external carbon sources for disinfection. The industrial symbiosis model focused on wastewater treatment systems at the level of industrial parks and has saved many costs and environmental benefits [28]. In 2020, Mohd Arif Misrol et al. developed a mathematical model to maximize the continuous benefits of water recycling and water integration in a superstructure wastewater management system [42]. Moreover, some researchers have worked on the synergy between water- Energy, and food nexus [21]. In this regard, a study has been developed to investigate the synergy potentials of water integration and solid waste utilization using Pareto optimization [18]. In this way, Chihhao Fan et al. conducted an integrated assessment model of water, Food, and Energy(WFE) deficiencies in the urban sector. In this regard, using a linear regression model and simultaneous equation model (SEM) and weighting of each of the main variables, different scenarios have been investigated such as population growth, technology-based development of agriculture, energy structure improvement, and access to water resources [13]. In 2020, Huang et al. described the structure of WFE in an urban area using a set of equations systems. In this study, the SEM method has been used instead of only one indicator to identify the nexus of different sectors, This method is an effective method for the exchange mechanism in the structure of Nexus, which can have more reliable results than recent work [29]. Besides, Schull VZ et al. modeled the water, energy, and food nexus with a view of water management. In this work, an agricultural watershed in northwestern India was surveyed using the WFE nexus framework. Spatial and temporal analysis of the water model was identified and studied using SWAT software. One of the main characteristics of this study was the evaluation of water quality using the water-energy and food nexus framework [52]. Saige Wang examined the effects of the water sector and energy-related decisions and developed an evaluation framework for the water and energy nexus scenarios by using of input-output table method to predict the future of the energy sector in China [57]. In 2019, Raphaël Payet-Burin et al. developed an open-source model of hydro-economic optimization. This model incorporates water, agriculture, and power systems with a holistic approach. In this model, they examined the potential and investments required to prioritize the development of hydropower generation, irrigation of the agricultural sector, and network connection [48]. In 2018, Kuang-Yu Yuan et al. introduced a way to minimize the environmental impact of development. In this method, considering the interactions between water, energy, and food, they have performed a spatial optimization for three energy products (rice, corn, and sugarcane) in four main scenarios of climate change. To this end, life cycle assessment, linear programming, and climate change simulation model have been integrated to develop the bioenergy production chain and due to the benefits of bioenergy, its development priorities have been identified according to the current renewable energy policy in Taiwan [60]. Integrating the study of consumption patterns and consumer behavior in the nexus framework can play an important role in reducing the overall impact of development on the environment in the future [40].

While Nexus provides a strong framework for interdisciplinary study, much research has been done on the "security" of regionally focused resources from a resource trade perspective, and in this regard, environmental impact assessment alone cannot be a set of relationships between natural underlying processes [11]. In Korea, a comprehensive study was done on the whole supply chain. The target of this project was Eco-industrial parks (EIP) development analysis in economic performance using the IoT method. They tried to enlighten the national financial system reforming and planning [14,47]. The economic power of the region is another lever of development, which should be provided by the regional potential. In this way, one of the economic perspectives of local development is regarding the local potential for tourism development. Unfortunately, in the 20th century, we faced major changes in technology, political, and economic changes in rural areas, and they have brought a large number of challenges in this area. Dorobantu et al. studied the sustainable development of local Romanian communities through ecotourism., and they tried to show the relationship between rural ecotourism development and some requirement in line with sustainable development in these regions [50]. Fan et al. used the eco-efficiency coefficient for resource, economy, and environment management toward sustainable development and showed that the scale and number of regions could change their performance [14].

One of the main risks of regional development is the barrier effect of development on ecosystem regeneration and restoration. So, it is so important to fill the gap between system enlargement, and ecosystem regeneration. A regenerative point of view can lead to an optimal interconnection between the system and the ecosystem to a large extent. Ecosystems that can recover, renew, or revive their energy, material, and information resources not only produce regenerative products that can be recycled but also lead to improving the environmental conditions during the product's life cycle. In this regard, Regenerative design seeks to address the ongoing degradation of ecosystems by developing the built environment to restore the capacity of ecosystems to function optimally in health for the mutual benefit of human and nonhuman life [10]. It can add an Ecosystem part to the water-Food, Energy nexus model. Biowaste management can augment the ecosystem regeneration approach. Tareq Al-Ansari et al. studied the relationship between the production and use of fertilizer and livestock, and the water system, which through mechanical and thermal desalination processes supplies water to agriculture demand and an energy subsystem, natural gas production, and renewable solar energy system [17]. The analysis shows that the food system is the biggest cause of global warming, and regional development [2].

Studies in the past have focused on a more systemic approach to river basin connectivity and global scale. The WEAP [59] LEAP tool combines an allocation energy system (LEAP) with a hydrology-agricultural model (WEAP-cropWat) [45]. This tool has been used in the context of the Tana River basin in Ethiopia [30] and California [59]. As a simulation (rather than an optimization tool) it is limited to exploring user-defined scenarios. CLEW1, GAEZ-WEAP-LEAP [27] was this type's first integrated modeling approach. It analyzed simultaneous scenarios of GHG reduction, adaptation, energy, water, and agricultural development. CLEW2 approach, GAEZ-WEAP-OSeMOSYS-MAMS includes an optimization in the energy sector using the Open-Source Energy Modeling System (OSeMOSYS), which enables the optimization of energy investments and their performance [53]. World Bank's Evaluating Climate Resilience (WBecr) approach is the most comprehensive to date [12]. It simultaneously assessed 8 major African river basins, agricultural plans, and more than 40 countries. The approaches are open source and allow dynamic optimization and trade-offs for water use in each basin. WE2F Nexus (UNECE) LISFlood-OSeMOSYS is the use of the LISFlood model [56] to create potential water production constraints in the OSeMOSYS model [26]. This tool considers not only the average hydrology but also the potential effects of flooding. ASBmm (ICWC), Aral Sea Basin Management Model (ASBmm) and BEAM [49] are software product basin economic allocation models, that are useful for evaluating projects and using water, land, and other natural resources. which provides the possibility of evaluating the social, ecological, and economic conditions of certain regions and countries. GAEZ Global Agro-Ecological Zones [16] is a global tool that helps calculate potential yields and water for up to 280 crop/land use types under alternative input and management levels for historical, current and future climate conditions. CLITools has been developed by MIT and Indecon [9]. These are open-source tools that allow dynamic optimization of water allocation, including optimization across crops. The BEAM model [49]estimates the welfare variation associated with changes in water allocation. OSeMOSYS is an open-source energy systems model. It is typically extended to include water, land and greenhouse gas emissions [26,3]. LISFLOOD [56] is a GIS-based hydrological precipitation and runoff model developed at the JRC. It includes a one-dimensional hydrodynamic channel routing model that is currently used to simulate water resources in Europe, Africa, and on a global scale.

Regional nexus modeling concerning the natural limitation is a challenge in most nexus models, which requires entering the structure of the soil, and other ecosystem elements' interaction in terms of social welfare in an optimization nexus approach. It can make a guarantee to development of the ecosystem regarding nature's limitations.

Regenerative design is an integral component of the ecosystem. In other words, Soil as one of the forgotten links of water, energy, and food nexus is another requirement to study. Soil is the cause of runoff transfer and infiltration into irrigated water, which is eventually given by the soil to green water for plant growth. In addition, soil plays an important role in the conversion of agricultural, animal, and tree waste into humus nutrients in the soil, which, of course, is ultimately used as nutrients for plant growth. The sludge of the water treatment process can also be used as plant nutrients. Contaminated water (gray and black) must be converted to blue and green water through filtration processes and then enter the soil [33]. In this respect, A multi-study model was developed in India. This model developed in different economic, social (population growth), and environmental aspects. Cooling technologies in the power plants are one of the most important items, which were used to estimate the optimum water withdrawal and the amount of CO2 reduction in the water-energy nexus framework. Moreover, the utilizing different types of electricity generation technologies and different renewable and fossil fuels were entered into the model and their interaction with water consumption was surveyed to make a strategy for policymakers [54].

The gap, aims, and objectives of the paper

Given that the Nexus approach originates from the understanding that water, energy, agriculture, and natural ecosystems have strong inter-linkages, and under a sectoral approach, it moves towards achieving resource security so that development takes into account Water, energy and food without the approach of mutual effects of ecosystem sustainability, the security of access to resources in the region may face risks due to future limitations. This study, to identify mutual links, synergies, and exchanges in an industrial area with the Nexus approach, to identify solutions, strengthening the security of access to resources in the future by considering economic drivers and increasing the efficiency of resource exploitation. Water, food, and energy, and reducing the effects and risks of development on ecosystems have been addressed in the agricultural sector (soil productivity considering the development of natural resources). In this regard, the integrated water-energy-food and ecosystem model has been developed with the Nexus approach to enable the analysis of mutual links between sectors and to provide positive synergy according to development potentials. This is done by adopting an integrated and coordinated approach across sectors to reconcile the potential of conflicting interests as sectors. Moreover, sensitivity analysis has considered the regional development options, which have the competition for access to scarce resources, while it has been identified and strengthened the current opportunities extremely dependent on the limitation, which leads to augment the ecosystems.

On the other hand, Soil is a non-forgotten section of nature. The unique natural organization of soil forms the foundation of any food-water-energy linkage system. It moderates the soil-water-plant-energy nexus by providing green water (from precipitation) to plants and soil organisms, which in turn enables the production of biomass as a source of food, feed, fiber, and biofuel. As a result, the soil is not only the basis for the provision of natural resources: food, water, and energy but also urgently needs to be integrated with understanding the complex interdependence of each food, energy, water, and soil system. Here, the ecosystem elements such as forest, and crop growth and their interaction with the soil have been considered as some systems, in which the human-made systems development affects the ecosystem elements' quality and growth.

In this study, according to the economic challenges in the studied area and the importance of ecotourism development, the effects of wastewater and solid waste pollution will be intensified. The economic development of the region requires the development of basic infrastructure and increases the operational capacity of the region. Moreover, the development of ecotourism causes the management of waste and sewage and its effect on the regeneration of the region in terms of making soil fertilizers, and the additional effects on the soil capacity improvement for the agricultural sector with regard to the available natural resources to support the production of organic materials.

On the other hand, the potential of exploiting energy resources in remote areas can provide the possibility of long-term investment in this sector with the participation of the private sector for the development of the region.

Methodology

Energy services, including lighting, heat, and power supply, are a vital demand for the development of societies. Rural areas often have minimal access to energy due to limited access to finance and development initiatives. While people in these areas also need the energy to meet their daily needs, to have a healthy and modern lifestyle, and to grow their level of economic activity. Residents of all these regions, including rural areas, should have an equal opportunity to access sustainable and affordable energy. In this project, we try to develop an integrated model for rural development, in which residential places are near the sea (Fig. 2). In this regard, First of all, after the data gathering process, it has been modeled all of the regional sectors (energy, water, agriculture, and soil), and it has been considered all interactions between different sections. Some constraints have been utilized in the model (demand and supply constraint, Maximum capacity development constraint, environmental impact constraint, resource input to the region limitation, etc.). it should meet the main current and predicted demand based on the population growth and the output of the eco-tourism model. A multi-objective model has been applied to select the optimum capacity for each technology in the region.

The objective function of an integrated agroecosystem model includes two main approaches: maximizing Value-added by developing the Shif region and minimizing environmental impacts(Eco-indicator 99 minimization [23,22]). Therefore, the optimization process should solve multi-objectives. A common method to evaluate a sustainable ecosystem is considering Eco-efficiency. The eco-efficiency of Eco-Industrial Park (EIP) is defined as the ratio of value-added to the environmental impact. This conceptual model has been developed to evaluate the integrated energy and environmental management system in Shif Island. The model has been extended to include industrial and non-industrial Water, Energy, Agricultural, and Waste supply chains. The non-Industrial water supply chain includes water withdrawal from the sea, water extraction from air humidity, and solar energy. Domestic sewage and wastewater, which are sent to the collection and treatment units and then stored in non-drinkable water storage tanks, are consumed in agriculture and as greywater. Tidal technology has been considered for power generation. The energy supply chain includes various technologies for power production, heat, and cooling. The connection of the integrated system to the national grid has also been assumed. The leading technologies represented in the model include, among other technologies such as PV, CHP, and waste power generation. Decentralized PV is used for lighting the streets, and the centralized PV electricity generation is sent to the local network. The transformation of Shif Island into an ecotourism zone is considered a prosperity factor for further development. The development of ecotourism shall lead to the expansion of economic and social activities, which would require expansion of the supply chain of goods and services, which would be associated with an impact on the environment. Ecotourism would require the minimization of waste discharge into the environment and the accretion of natural resources. Therefore, the present study aims at maximum recycling and reuse wastes and utilization of renewable energy sources. The development of agriculture in the region would be modeled with the help of the Liebig law, and the growth rate of agricultural products is optimized subject to the limitation of nutrients. Furthermore, the interactions between soil, atmosphere, and biosphere are modeled in order to identify the path of sustainable development of land use (Fig. 1). Formally, the relative eco-efficiency of $\mathrm{EIP_k}$ can be calculated as follows [36]:

$$\boldsymbol{EE} = \max\left(\frac{\boldsymbol{y}}{\sum_{i=1}^{m}\boldsymbol{w_i x_i}}\right) \tag{1}$$

$$\begin{aligned} s.t.\ \frac{\boldsymbol{y}}{\sum_{i=1}^{m}\boldsymbol{w_i x_i}} &\le 1, \forall j = 1,2,\dots,N. \\ \boldsymbol{w_i} &\ge 0,\ \forall i = 1,2,\dots,m \end{aligned} \tag{2}$$

$\boldsymbol{EE}$: $\mathbf{Eco-efficiency}$
$\boldsymbol{y}$: $\mathbf{Value-added}$
$\boldsymbol{w_i x_i}$: $\boldsymbol{Environmental\ impact}$

Relative eco-efficiency has been defined as a non-dimensional indicator, and it is defined as follows [37]:

$$\boldsymbol{EES} = \frac{\boldsymbol{EE}}{\boldsymbol{EE^{max}}} \tag{3}$$

$\boldsymbol{EES}$: Eco-efficiency Score (Eco-efficiency measured)

$\boldsymbol{EE^{max}}$: $\boldsymbol{The\ Maximum}$ $\mathbf{Eco-efficiency}$, which is observed in all EIPs

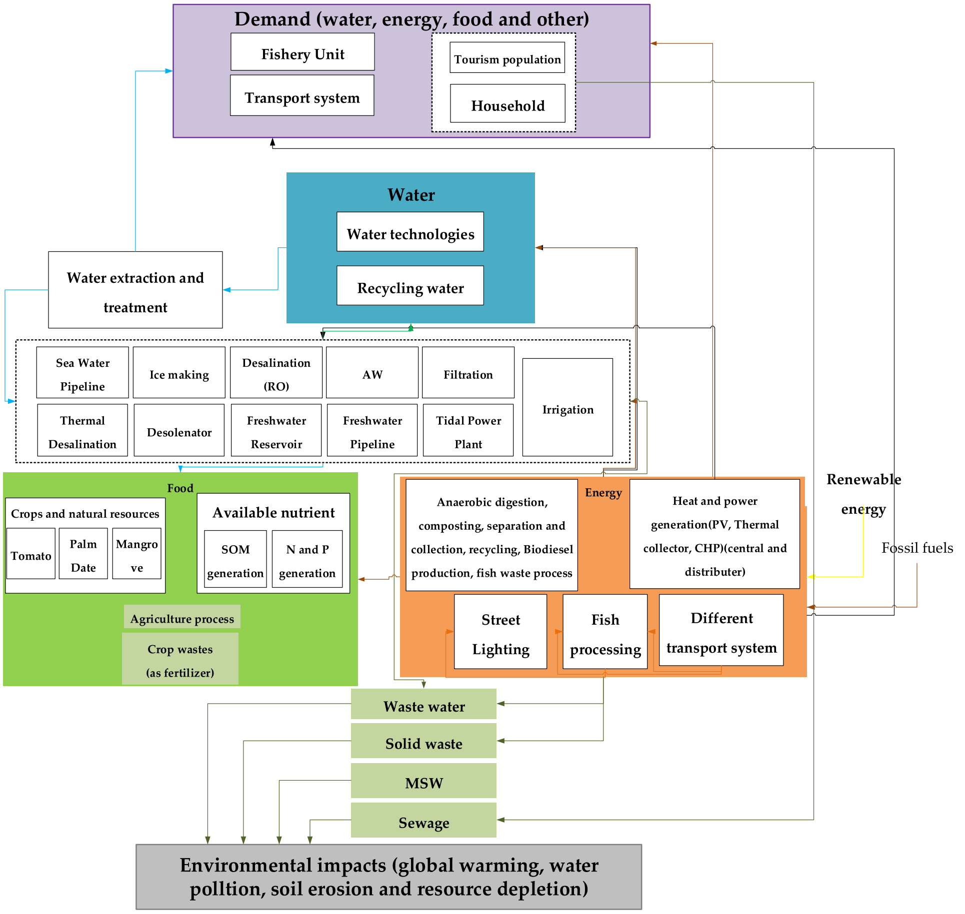

Fig. 1. The framework of eco-industrial park in Shif Island.

Variability of the environmental impact may be estimated with the help of minimizing Eco-indicator 99 for a given probability level. The definition of this performance measure increases the level of probabilistic constraint:

$$\Pr\left[ECO_{99} \le \Omega\right] \ge K \tag{4}$$

The deterministic equivalent of this probabilistic constraint can be obtained by using chance-constrained programming [35,55]. Specifically, by subtracting the mean ($\widehat{Eco99}$) and dividing it by the standard deviation of the Eco-indicator 99 (ECO_{99}^{SD}), the chance constraint, normalized function, and the final equation can be written as:

$$\Pr\left[\frac{ECO_{99} - \widehat{Eco99}}{ECO_{99}^{SD}} \le \frac{\Omega - \widehat{Eco99}}{ECO_{99}^{SD}}\right] \ge K, \tag{5}$$

$$\phi\left(\frac{\Omega - \widehat{Eco99}}{ECO_{99}^{SD}}\right) \ge K \tag{6}$$

$$ECO_{99}^{SD}\,\phi^{-1}(K) + \widehat{Eco99} \le \Omega \tag{7}$$

The general objective function can be changed as:

$$\max\left(\left(EES = \frac{\mathrm{VA}_{\mathrm{final}}/\mathrm{Eco} - \mathrm{indicator}\ 99}{EE_{max}}\right), -\Omega\right) \tag{8}$$

In all technologies, first, according to the conversion efficiency of the material, the amount of material required can be calculated. Next, according to the concentration of substances in the different mass flows, the final concentration of the substance has been estimated. Moreover, the amount of energy consumed through consumption factors is entered

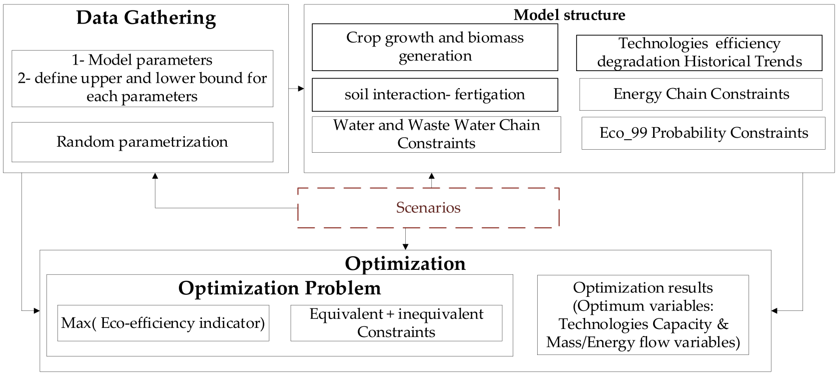

Fig. 2. Model structure of this paper.

into the model as a coefficient of mass input proportional to production. The carbon emission of each stream has been generated based on energy consumption.

$$\boldsymbol{TM}_{i,out,t} = \boldsymbol{TM}_{i,in,t} \times \eta_{i,t} \tag{9}$$

$$\boldsymbol{X}_{out,i,t} = \boldsymbol{WM}_{i,in,t} \times \eta_{C,i,t} \tag{10}$$

$$\begin{aligned} \boldsymbol{TE}_{i,output,t} = {} & \boldsymbol{TE}_{i,input,t} \times \eta_{i,energy,t} + \boldsymbol{TM}_{i,in,t} \times \eta_{i,energy,t} \\ & \times \boldsymbol{elec\ factor}_{i,energy,t} \end{aligned} \tag{11}$$

$$\boldsymbol{EXL}_{i,t} = \boldsymbol{TE}_{i,input,t} \times \boldsymbol{emission\ factor}_{i,t} \tag{12}$$

Where, $\boldsymbol{TM}$ is the mass flow for each technology, i are different technologies(Air-water generation, Tidal power plant, Freshwater pipeline, Freshwater Reservoir, Seawater pipeline, Desalination technologies (Reverse Osmose, Thermal desalination, desolenator), Filtration, Undrinkable water pipeline, Undrinkable water Reservoir, Algae Harvesting, Fish waste process, Biodiesel production, Waste process, Anaerobic Digestion, Composting process, Waste conversion, Recycling, Ice making, Fish processing), X is the concentration of the different substance in streams, TM is the mass flow in different technology, TE is the energy flow in different technology, $\boldsymbol{\eta}$ indicates the efficiency of different technology for energy and material conversion, $\boldsymbol{elec\ factor}_{i,energy,t}$ is used to estimate the electricity consumption per mass input, EXL illustrates the carbon emission of each technology, in and out are the input and output flow, and consequently, t indicates the time horizon of the project.

The capacity of each technology has been chosen as:

$$\boldsymbol{CT}_{i,t} + \boldsymbol{NCT}_{i,t} \leq \frac{\mathbf{HCT}_{i,t}}{\eta_{i,t}} \tag{13}$$

CT, NCT, and HCT are the current, new, and historical technology capacity, respectively.

It means that the technology capacity selection has been determined considering historical capacity and new required capacities.

Depending on the amount of material and energy required, the sum of all resources that can produce materials and energy shall always be less than the total amount of production. In other words, another constraint relates to the supply and demand constraints throughout the system. Under this limitation, all the energy required by the system, the energy, and material required by the system must be supplied through existing technologies and input resources for studies.

$$\sum_{t=1}^{20} \sum_{i} \boldsymbol{TM}_{i,in,t} \leq \boldsymbol{TM}_{demand,total,t} \tag{14}$$

Another limitation is the capacity of each technology. According to the technologies available in the market, a limitation of the high capacity for technologies has been selected for each technology:

$$\boldsymbol{CT}_{i,t} \leq \boldsymbol{\alpha}_{i} \tag{15}$$

Here, $\boldsymbol{\alpha}$ is the upper limit of each technology.

On the other hand, each technology produces some waste and effluent. Each of these streams has been converted into energy, water, and materials according to waste management technologies. Each of these technologies is also included in this model. the model of agriculture and natural ecosystems includes the annual growth rate of tomatoes, dates, mangroves, and grassland species. In the agriculture ecosystem, constraints on nutrients change the growth rate of agricultural species, which enables the projection of agricultural products. Michaelis-Menten method (as a developed Liebig law) and biomass generation factor have been used for evaluation of the growth of agrarian product and biomass generation, respectively. The rate of biomass generation is used to calculate the rate of depletion of natural resources. The rate of depletion of mangrove forests is therefore estimated based on [4]. The main constraints of nutrients are related to the demand for nutrients required for sustaining plant growth. On the other hand, the concentration of the nutrient is increased because of the rate of waste decomposition in the soil due to waste production by population growth in the area. The minimum amount of nutrients required and the amount of nutrients added to the soil over time determine the amount of demand for nutrients. Variation of soil SOM concentration depends on different types of the pool(Non-woody biomass, Woody biomass, Litter, CWD, Fast, Slow, and Passive SOM) [6,7,34,39]. The transient dynamics of terrestrial carbon storage are determined by two components: the C storage capacity and the C storage potential [38]. Table 1 shows different interactions between Soil- Crop in this study.

Per FOREMAN model is used for the mangrove forest growth, is based on soil salinity, nutrients availability, temperature, and light radiation. The growth equation of this model is as Table 2 [24]. More detailed data on this method has been illustrated in Appendix A.

Regarding different interactions in different technologies and different ecosystem interactions, the main roadmap of developing this system has been proposed in this paper.

Results and discussion

Interactions between different sectors in Shif Island are shown in Fig. 1. The figure also indicates different technologies that can be applied in the region. The model structure of various technologies is presented in the appendix. The concept of Water-Energy and Food interactions (WEF) has emerged in response to the climate change impacts and the social changes, e.g., population growth, globalization, economic growth, urbanization, growing inequalities, and social dissatisfaction. These issues put more pressure on water, energy, and food resources. In this section, the results of two main scenarios based on Table 3; an eco-industrial park and ecotourism rural region have been illustrated, and the effects of these developing approach in Shif Island development has been discussed.

Study area

Shif island is a small rural region near the Persian Gulf (Fig. 3). It is located north of Bushehr Port and at the end of Helleh wetland, which is composed of the interconnection of Shapour and Dalaki rivers. A particular characteristic of this island is that about 40% of the island is affected by tidal streams.

The special feature of this island is that about 40% of the island is affected by tidal currents. Shif Island is a coastal area and has a high potential for tourism development. Due to the lack of proper management, in recent decades, not only the number of tourists in this area has decreased, but the area itself has also suffered widespread destruction. So, in this research, taking into account the potential of the region's ecosystem and its development requirements, it has been investigated.

Different technology development in the rural region (Shif Island)

In this model, recycling, composting, and energy generation processes are reviewed as the relevant waste management technologies in Shif Island. Like this model, about 45% of urban waste (food waste) is suggested using as compost, 30% use in the recycling process, and a small percentage of waste can be utilized in the energy production unit.

The number of available nutrients based on agricultural production and land productivity is calculated according to Liebig Law. Phosphorus, nitrogen, and potassium are the most important nutrients for plant growth. According to the Liebig Law (minimum level of nutrient requirements for plant growth), the plant nutrient demand, its accumulation in the land, and the nutrient changes can be measurable. In this study, biomass generation as a source of nutrients has been used, and in the

Table 1
Different interaction between Soil- Crop.

Equation	Equation number	Description
$\boldsymbol{Crop}_{1t} = \sum_{i=1}^{2} \begin{matrix} \boldsymbol{Minimum}_i(\boldsymbol{AY}_{max,i,t}, \boldsymbol{N}_i,\ \boldsymbol{P}_i, \boldsymbol{K}_i, \boldsymbol{t}), \\ i = 1(\boldsymbol{tomato}),\ 2(\boldsymbol{date},\ \boldsymbol{tree}) \\ N(\boldsymbol{Nitrogen}), P(\boldsymbol{Phosphorus}), K(\boldsymbol{potassium}) \end{matrix}$ [1]	(16)	Crop Growth function($\boldsymbol{Crop}_{1t}$) developing grassland and mangrove forest ecosystems depend on their cultivation factors and nutrient limitation [15]. $\boldsymbol{CF}$: **cultivation factor**.
$\boldsymbol{U}_{i_t} = \boldsymbol{Biomass\ factor}_i \times\ \boldsymbol{Crop}_{i_t}, (\boldsymbol{i = date\ tree,\ tomato\ and\ grassland}),$	(17)	Michaelis-Menten method (as a developed Liebig law) used for crop growth and nutrient limitation
$\boldsymbol{Crop}_{i,t} = \boldsymbol{CF}_{i,t} \times \boldsymbol{Area}_{ag_{i,t}}\ (\boldsymbol{i} = 3(\boldsymbol{grassland}),\ 4(\boldsymbol{mangrove\ forest})$	(18)	$\boldsymbol{Area}_{ag_{i,t}}$: ***cultivating area*** $\boldsymbol{AY}_{max,i,t}, \boldsymbol{N}_i,\ \boldsymbol{P}_i, \boldsymbol{K}_i, \boldsymbol{t}$: Maximum growth rate
$\boldsymbol{U}_{4t} = \frac{\boldsymbol{a}-1}{\boldsymbol{a}-\boldsymbol{a}^{t-T}} \times \frac{\boldsymbol{a}^{T+1-t}-1}{\boldsymbol{a}^{T+1}-1}\boldsymbol{S}_{t-1},$ $\boldsymbol{a} = 1.02(\textbf{unsustainable}),\ 1.05(\textbf{limited sustainable})$ $,\ 1.1(\textbf{sustainable})$	(19)	For mangrove forests, biomass generation is based on the prediction of depletion of natural resources [32].[2] $\boldsymbol{S}$: ***natural resource stock***
$\mathbf{X_i(t)} = (\sum_{\mathbf{j=1}}^{\mathbf{n}} \mathbf{f_{ij}b_ju(t)} - \sum_{\mathbf{j=1\ j\neq i}}^{\mathbf{n}} \mathbf{f_{ij}}\boldsymbol{\tau}_\mathbf{i}\mathbf{x_j}') \times \boldsymbol{\tau}_\mathbf{i}$	(20)	$\boldsymbol{f}_{ij}$ is a fraction of C transferred from pool j to i through all the pathways, $\boldsymbol{b}_j$ is a partitioning coefficient of C input to the jth pool, $\boldsymbol{u}(\boldsymbol{t})$ u(t) is C input rate, $\boldsymbol{\tau}_i$ measures residence times of individual pools in isolation, $\boldsymbol{x}_j'$ is the net C change in the jth pool, $\boldsymbol{X}_i(\boldsymbol{t})$ is the C storage in the i^{th} pool. The first term on the right-hand side of the above equation is the C storage capacity, and the second term is the C storage potential[3].
$\mathbf{xj}'(\boldsymbol{t}) = \frac{\boldsymbol{X}_{p,i}(\boldsymbol{t})}{\boldsymbol{\tau}_i}, \mathbf{xj}' = \boldsymbol{constant}, \mathbf{xj}' =\ [1; 1; 1; 0.91; 0.21; 0.23; 0.79; 0.93]$ $\boldsymbol{\tau}_i = \frac{\boldsymbol{X}_{p,i}(\boldsymbol{t})}{\mathbf{xj}'(\boldsymbol{t})}$ [4]	(21)	$\mathbf{xj}'(\boldsymbol{t})$ is the variation of carbon concentration in each pool. $\boldsymbol{\tau}_i$: **Residence time**, $\boldsymbol{X}_{p,i}(\boldsymbol{t})$ is the sum of all the individual net C pool changes. In mangrove forest, carbon efficiency and carbon canopy (annual carbon capture) are 0.33 and 032, respectively [5]
$\mathbf{u}_t = \mathbf{mangrove}_{\mathrm{C}_{\mathbf{canopy}_t}} + \mathbf{grassland}_{\mathrm{C}_{\mathbf{canopy}_t}}$	(22)	Carbon canopy is the sum of mangrove and grassland carbon canopy. $\mathbf{u}_t$ is C input rate
$\mathbf{Nr}_{\mathbf{P}_t} = \mathbf{C}_{\mathbf{SOM}_t} \times (\frac{1}{\mathbf{CP}}),\ \mathbf{Nr}_{\mathbf{N}_t} = \mathbf{C}_{\mathbf{SOM}_t} \times (\frac{1}{\mathbf{CN}}),$ $\mathbf{CN} = [16; 13; 7.9],$ $\mathbf{CP} = [110; 320; 114](\textbf{six scenarios})$ [19]	(23)	Biomass SOM can be used for calculating nitrogen and phosphorous concentrations in soil. $\mathbf{Nr}_{\mathbf{P}_t}$:P concentration in residue; $\mathbf{C}_{\mathbf{SOM}_t}$:carbon concentration in soil (SOM size); **CP**:C to P ratio; $\mathbf{Nr}_{\mathbf{N}_t}$: N concentration in residue; **CN**: C to N ratio
$\boldsymbol{N}_{app_t} = \sum_{i=1}^{4} \boldsymbol{Compost}_{f_i,t} \times \boldsymbol{Crop}_{i,t} \times \boldsymbol{N}_{C,i} + \boldsymbol{Fertilizer}_{f_i,t} \times \boldsymbol{Crop}_{i,t} \times \boldsymbol{N}_{f,i},$	(24)	The amount of nutrients is obtained from fertilizers and compost. $\boldsymbol{N}_{app_t}$: applied nitrogen $\boldsymbol{N}_{C,i}$: nitrogen concentration of compost $\boldsymbol{N}_{f,i}$: nitrogen concentration of fertilizer
$\boldsymbol{P}_{app_t} = \sum_{i=1}^{4} \boldsymbol{Compost}_{f_i,t} \times \boldsymbol{Crop}_{i,t} \times \boldsymbol{P}_{C,i} + \boldsymbol{Fertilizer}_{f_i,t} \times \boldsymbol{Crop}_{i,t} \times \boldsymbol{P}_{f,i}$	(25)	$\boldsymbol{P}_{app_t}$: applied phosphorus $\boldsymbol{P}_{C,i}$: phosphorus concentration of compost $\boldsymbol{P}_{f,i}$: phosphorus concentration of fertilizer
$\boldsymbol{P}_{J,t} = \boldsymbol{P}_{app_t} + \boldsymbol{Nr}_{P,t},\ \boldsymbol{N}_{J,t} = \boldsymbol{N}_{app_t} + \boldsymbol{Nr}_{N,t}$ $\boldsymbol{N}_{dec_t} = \boldsymbol{k}_{J,1} \times \boldsymbol{N}_{J,t} \times \boldsymbol{r}_\theta \times \boldsymbol{r}_t,\ \boldsymbol{k}_{J,1} = 0.0438,\ \boldsymbol{r}_\theta, \boldsymbol{r}_t = 1$ $\boldsymbol{P}_{dec_t} = \boldsymbol{k}_{J,2} \times \boldsymbol{P}_{J,t} \times \boldsymbol{r}_\theta \times \boldsymbol{r}_t,\ \boldsymbol{k}_{J,2} = 0.00438,\ \boldsymbol{r}_\theta, \boldsymbol{r}_t = 1$	(26)	$\boldsymbol{N}_{dec_t}$ ***and*** $\boldsymbol{P}_{dec_t}$ ***are*** decomposed amounts of N and P. $\boldsymbol{N}_{J,t}$and $\boldsymbol{P}_{J,t}$ are pool sizes (gm^{-2}) of nitrogen and phosphorus, respectively (j from 1 to 7 represents the soil organic matter pools: CWD, metabolic litter, cellulose litter, lignin litter, fast soil organic carbon (SOC), median SOC, slow SOC); $\mathbf{N}_{\mathbf{dec}_t}$, $\mathbf{P}_{\mathbf{dec}_t}$ are N and P decomposition; $\mathbf{k}_{\mathbf{J},1}$, $\boldsymbol{k}_{J,2}$ are the rate constant of soil organic matter decay (s^{-1}) $\mathbf{r}_\theta$, $\mathbf{r}_\mathbf{t}$ (dimensionless) are soil temperature and moisture environmental regulators
$\boldsymbol{F}_{N_{mob_t}} = \sum_{j}^{n} \boldsymbol{N}_{dec_t} \times \max(\frac{1}{\boldsymbol{CN}} - \frac{\boldsymbol{g}_i}{\boldsymbol{CN}}, 0) \times \boldsymbol{f}_{ij},\ \ \boldsymbol{F}_{P_{mob_t}} =$	(27)	Mobilization, immobilization (mineralization), leaching, nitrogen loss, deposition, phosphorous surface loss, occlusion, Soil nutrient demand, and depletion of different nutrient resources
$\sum_{j}^{n} \boldsymbol{P}_{dec_t} \times \max(\frac{1}{\boldsymbol{CP}} - \frac{\boldsymbol{g}_i}{\boldsymbol{CP}}, 0) \times \boldsymbol{f}_{ij}$	(28)	$\boldsymbol{g}_i$ is the Percentage of carbon that remains in the soil after decomposition of ith SOM
$\boldsymbol{F}_{N_{immob_t}} = \sum_{j}^{n} \boldsymbol{N}_{dec_t} \times \mathbf{max}(\frac{\boldsymbol{g}}{\boldsymbol{CN}} - \frac{1}{\boldsymbol{NN}}, 0)\ \times \boldsymbol{f}_{ij},\ \boldsymbol{F}_{P_{immob_t}} =$	(29)	$\boldsymbol{F}_{N_{mob_t}}$, $\boldsymbol{F}_{P_{mob_t}}$ are mobilization fluxes of soil mineral nitrogen and phosphorus $\boldsymbol{F}_{N_{immob_t}}$, $\boldsymbol{F}_{P_{immob_t}}$ are immobilization fluxes of soil mineral nitrogen and phosphorus
$\sum_{j}^{n} \boldsymbol{P}_{dec_t} \times \mathbf{max}(\frac{\boldsymbol{g}}{\boldsymbol{CP}} - \frac{1}{\boldsymbol{CP}}, 0)\ \times \boldsymbol{f}_{ij}$	(30)	CN is Soil organic matter CN ratio $\boldsymbol{CP}$ is Soil organic matter CP ratio
$\boldsymbol{Ne}_{N_t} = -\boldsymbol{N}_{dec_t} + \boldsymbol{F}_{N_{mob_t}} + \boldsymbol{F}_{N_{immob_t}},\ \boldsymbol{Ne}_{P_t} = -\boldsymbol{P}_{dec_t} + \boldsymbol{F}_{P_{mob_t}} + \boldsymbol{F}_{P_{immob_t}}$	(31)	$\boldsymbol{Ne}_{N_t}$, $\boldsymbol{Ne}_{P_t}$: nutrient erosion(P: phosphorus and N: nitrogen)
$\boldsymbol{Ne}_{g_t} = 0.006 \times \boldsymbol{N}_{J_t}$	(32)	$\boldsymbol{Ne}_{g_t}$: gaseous nitrogen loss
$\boldsymbol{F}_{N_{dep_t}} = \frac{\boldsymbol{N}_{app_t}}{\boldsymbol{K}_{dep_{pot}}(1 + \frac{\boldsymbol{N}_{app_t}}{0.11} + \frac{0.000125}{2} + \frac{\boldsymbol{F}_{N_{immob_t}}}{0.04 \times 1000} + \frac{0.0012}{0.011})}$ $\boldsymbol{F}_{surf_{P_t}} = \frac{133 \times 64}{0.01 \times (64 + \boldsymbol{P}_{app_t})^2}$ $\boldsymbol{F}_{occl_{p_t}} = \boldsymbol{K}_{occl} \times \boldsymbol{P}_S,\ \boldsymbol{K}_{occl} = 12 \times 10^{-6},\ \boldsymbol{P}_S = 0.2$	(33)	$K_{dep_{pot}}$: deposition reaction coefficient $F_{surf_{P_t}}$ is the adsorption flux $F_{occl_{p_t}}$ is P occlusion flux $\boldsymbol{K}_{occl}$ is P occlude rate $\boldsymbol{P}_S$ is sorbed P content
$\boldsymbol{N}_{D_t} = \boldsymbol{N}_{app_t} + \boldsymbol{Ne}_{g_t} + \boldsymbol{Ne}_N + \boldsymbol{F}_{leaching_N} + \boldsymbol{F}_{dep_N},\ \boldsymbol{P}_{D_t} =$ $\boldsymbol{P}_{app_t} + \boldsymbol{Ne}_P + \boldsymbol{F}_{leaching_P} + \boldsymbol{F}_{surf_P} + \boldsymbol{F}_{weathering} + \boldsymbol{F}_{occl_P}$ $\boldsymbol{N}_{DP_t} = \boldsymbol{Ne}_g + \boldsymbol{Ne}_N + \boldsymbol{F}_{leaching_N} + \boldsymbol{F}_{dep_N},\ \boldsymbol{P}_{DP_t} =$ $\boldsymbol{Ne}_P + \boldsymbol{F}_{leaching_P} + \boldsymbol{F}_{surf_P} + \boldsymbol{F}_{weathering} + \boldsymbol{F}_{occl_P}$	(34)	$F_{leaching_N}$ is nitrate leaching $F_{weathering}$ is lost Parent material by weathering $P_{D_{P_t}}$: depletion of P $F_{leaching_P}$: leaching of P

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[1] The trend of maximum yield of tomato, date, mangrove and grassland growth predicts by FAO data [15].

[2] The trend of maximum yield of tomato, date, mangrove and grassland growth predicts by FAO data [15].

[3] In fact, this equation shows that at a given time, the amount of carbon in each pool is calculated from the difference between carbon storage capacity and carbon storage potential.

[4] $$\boldsymbol{X}_{p,i}(\boldsymbol{t}) = \begin{bmatrix} 0.00 & 0.00 & 0.00 & 0.00 & 0.00 & 0.00 & 0.00 & 1.00 \\ 0.00 & 0.00 & 0.00 & 0.00 & 0.00 & 0.00 & 1.00 & 0.00 \\ 0.00 & 0.00 & 0.00 & 0.00 & 0.00 & 1.00 & 0.00 & 0.00 \\ 0.00 & 0.00 & 0.00 & 0.00 & 0.91 & 0.80 & 0.38 & 0.02 \\ 0.00 & 0.00 & 0.00 & 0.21 & 0.00 & 0.00 & 0.91 & 0.00 \\ 0.00 & 0.00 & 0.23 & 0.22 & 0.88 & 0.57 & 0.60 & 0.01 \\ 0.00 & 0.79 & 0.25 & 0.23 & 0.52 & 0.30 & 0.89 & 0.00 \\ 0.93 & 0.88 & 0.16 & 0.22 & 0.32 & 0.20 & 0.87 & 0.01 \end{bmatrix}.$$

Table 2
The mangrove forest growth based on soil salinity, nutrients availability, temperature, and light radiation.

Equation	Equation number	Description
$\frac{dD}{dt} = \frac{GD(1-\frac{DH}{DH_{maxH_{max}}})}{274+3b_2D-4b_3D^2} \times S(salt).N(NUT).T(DEGD).r(AL)$	(35)	Per FOREMAN model
$S(salt) = \frac{1}{1+\exp(d(U_i - U))}$	(36)	The growth multiplier of salinity in FORMAN [24] U: Constant for salt effect on growth (g/kg)
$N(NUT) = c_1 + c_2RNA + c_3RNA^2$	(37)	constrain the growth of plants in response to nutrient availability [58] $c_{1,2,3}$ are constants; The nutrient availability index (RNA) is the ratio of phosphate concentration to the maximum phosphate content.
$T(DEGD) = 1 - (\frac{DEGD_{min}}{DEGD})^2$	(38)	The temperature multiplier T (DEGD) in the FORMAN model describes the global effect of climate on mangrove growth [51]. $DEGD_{min}$: Minimum growth degree days $DEGD$: growth degree days
$CF_t = CF_{t-1} \times \frac{dD}{dt}$	(39)	Mangrove growth rate (dD/dt) is related to the cultivating factors in different periods (productivity levels). If the condition is ideal, the productivity level is equal to 1, and various factors such as salinity, nutrients availability, heavy metals, and climatic factors can change the mangrove forest productivity levels.

Table 3
Scenario description in the studied area.

Scenario	Description
Scenario I	Eco-industrial park development (zero waste) without tourism development
Scenario II	Eco-industrial park development (zero waste) regarding eco-tourism development

long- term, urban and industrial waste disposal and population mortality increase the nutrient content of the soil. Two population growth scenarios (with and without ecotourism) can generate municipal waste. Commonly, municipal waste is a mixture of food, wood, paper, fibers, and textiles, and plastics waste. Also, a part of urban waste could be recovered as energy resources. For example, compost generation of food waste, electrical energy of wood and paper waste, and a part of the waste can be recovered and recycled, such as plastics. In terms of tourism development, from 2017, tourists are taking account as a source of value-added in this region, then the waste generation increases as a steeper. In the last year, waste generation was about 405 tons in the ecotourism development scenario, and, in the same year, in the absence of tourism development, 151 tons of waste was produced. In the industrial sector, by increasing population growth (ecotourism), the fish processing capacity can increase. Consequently, the amount of energy carrier production (as biodiesel) due to fishery waste will increase.

Given the region's potential, Shif Island has the potential to develop an ecotourism area with a capacity of about 2067 tourists. To meet the demand for tourism, it is necessary to identify the needed resources according to the potential of the region. As Fig. 4, It can be seen that the amount of required demand by the region is increasing as the increase's population. Non-domestic water, which is mostly related to industrial (fishing) activities, has a growing trend according to the potentials of the region.

Due to the population increase in the early years, the lower capacity of technologies (desolanator, RO, and thermal desalination) has been selected. Furthermore, population increase and the need for a larger capacity of freshwater generation system, the centralized thermal water

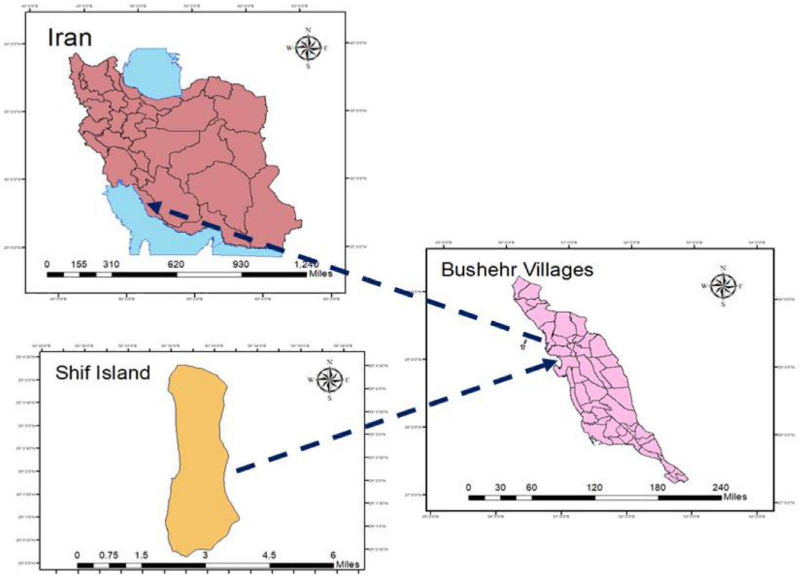

Fig. 3. The location of the study area.

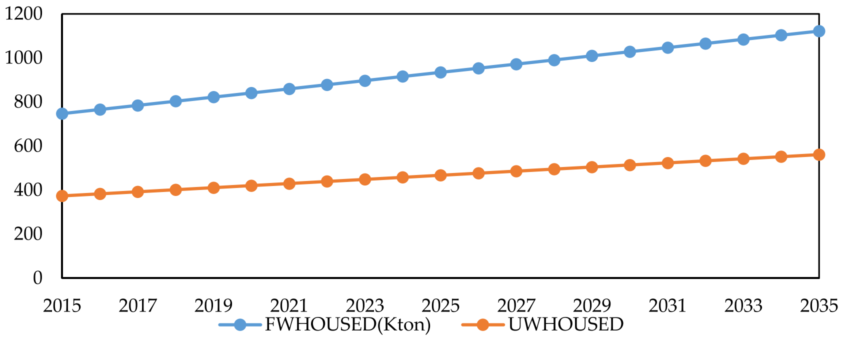

Fig. 4. Water demand increment with ecotourism development.

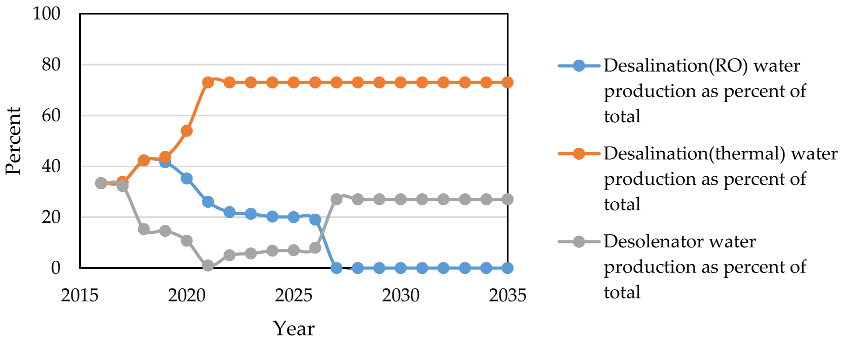

Fig. 5. Water desalination system in the case study.

desalination system has been selected. It is worth noting that thermal desalination technology has been selected as a centralized clean technology due to the use of solar energy (*Fig. 5*).

Given the importance of food security and ecosystem quality, land use limitations have become very important in recent years. The optimal land allocation is 45% of the total area for the rural population, 14% related to tourism development infrastructure, 10% for algal cultivating, 9% for urban waste management, 8% for industrial waste management and biodiesel production, 5% for desalinating, 5% Ice production, 4% of fish processing and less than 1% of the wastewater treatment unit.

Furthermore, rural and tourist population growth are the main contributors to the carbon footprint in this region. Based on the modeling results, from 2017, the carbon footprint of tourism development has increased. In contrast, the carbon footprint of urban populations has decreased, and from 2025, the percentage of carbon emissions of tourists will increase. In the last year, 63% of carbon emissions were due to tourist development. Carbon sinks include the atmosphere, algal cultivating, the sea, and photosynthesis processes. Over 20 years, 31 percent of carbon is released into the atmosphere, the sea absorbs 31 percent, 28 percent is absorbed in the algae cultivating process, and 10 percent carbon is absorbed in the photosynthesis process.

Waste management technologies will be selected from the first year to 2018, and water desalination technologies and other sustainable ecosystem development technologies will be developed to significant capacity by 2025, and agriculture will be developed from 2025 to 2030. The presence of tourists on the island is recommended from the first year, although, the development of tourism changes the amount of value added by less than one percent.

In this regard, the rural value-added changes under the developing economic activities in that village are illustrated in Figs. 6 and 7. It is shown, developing an efficient industry could increase the value-added in this village considerably. Other activities are not as effective as fishing when it comes to the development of the village. These means where the suitable activity in the village is identified (based on Agro-Complex), which can lead to considerable economic potential for the village.

Ecosystem flow analysis in optimum model in terms of resource nexus

For developing a sustainable eco-industrial region, maximizing eco-efficiency should show that all of the input and the output material and energy flow in Shif Island have been managed and organized. It means that the most important flow analysis includes the value of streams, the amount of resources withdrawal, and waste discharge to the environment. The results illustrate that in the optimal mode, how many resources will be destroyed and discharged into the atmosphere. In the next step, the analysis of mass flows is considered in different supply chains.

Throughout the last year, water withdrawal from the sea would reach 2000 tons. The change/variations in the number of different elements and compounds such as magnesium, calcium, salt, nitrate, and phosphate in seawater discharge and input are estimated for the last year. Throughout the same year, the optimum level of sewage discharge to the sea is estimated up to 34 tons per year. The cumulative amount of these compounds and elements in these 20 years are presented in Table 4.

The most important nutrients for plant growth are nitrogen, phosphorous, and potassium. Therefore, estimating their current and required concentrations for plant growth has crucial importance.

In this regard, considering the low concentration of nutrients in the soil by 2030, agriculture development is not suggested suitable. From this year forth, the nutrient could be supplied using sewage discharge, dead organisms' decomposition, and composting process with adding fertilizers. In the next step, the concentrations of heavy metals (Ni, Zn, and Cd) are estimated in the first and last years, and finally, the cumulative levels of said elements and the number of nutrients that leave the system boundaries (Shif Island) like agricultural products are determined (Table 5).

Table 4
Mass balance in hydrosphere in the last year.

Material	Input (seawater)	Discharge (to Seawater)	Accumulation
TDS (kg)	70,000	300,126.54	230,126.54
COD (kg)	2	273,775.64	273,773.64
BOD (kg)	—	19,848.73	19,848.73
Ca(kg)	832	21,286.06	20,454.06
Mg(kg)	2588	19,814.51	17,226.51
sulfate(kg)	5424	20,190.95	14,766.95
Nitrate(kg)	0.09672	1574.21	1574.11
Cl(kg)	38,706	…	…
salinity(kg)	804,000	813,068.82	9068.82

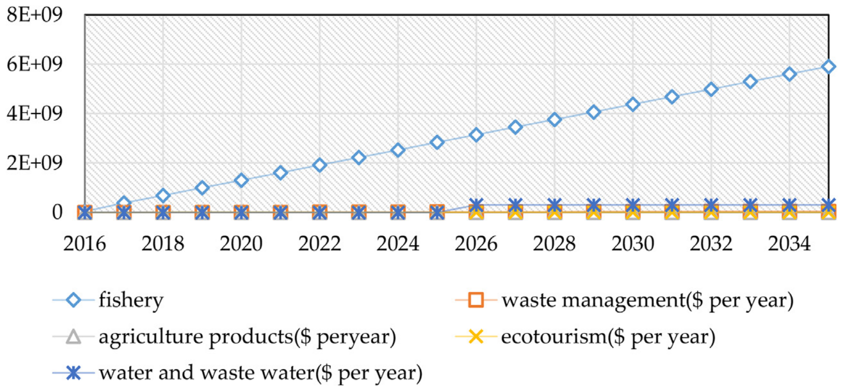

Fig. 6. Value-added variation based on developing technologies in this rural region.

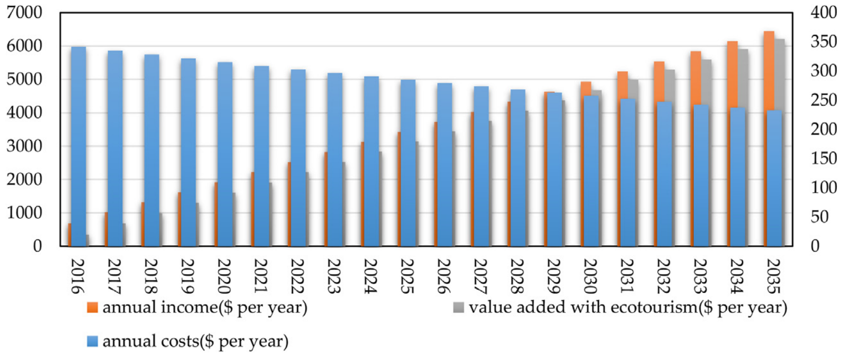

Fig. 7. Economic analysis of nexus model in the case study.

Different materials in this region can be predicted as different methods. Available nutrients, water, and energy have been explained in the next sections.

Eco-Industrial Park- Zero Municipal solid waste(MSW)

One of the most important issues in Shif Island is the lack of waste management technologies. In order to develop this region and transform it into a green and sustainable one, waste management is necessary. In the structure of the main model, the discharge rate to the environment should be lower than the permissible limit.

In this scenario, the main structure of the waste management technology model has been taken into consideration. The optimal capacity of the units has been determined based on the amount of waste production. The optimum discharge rate of the landfill is very low, and it does not make significant environmental impacts. It makes a little difference to the first optimum model because of environmental effects (Fig. 8).

The value-added generation in the region has increased the investment in industrial activities. The fishery is the dominant activity in the region, which can bring a lot of economic potential to the region. The lack of an ice-making system in the region has limited the revenue from this activity in the base year. So, in the present model, due to the development of the ice-making system in the region, this industry has developed in the region. The development of this industry causes the production of a lot of valuable waste (fertilizer and energy generation) in the region (Fig. 9).

Waste- Water and energy nexus in the regional level

One of the priorities of regional development is to minimize the waste discharged into the environment through the high value-added products in the region. In Fig. 10, the amount of waste generated from different sections (agriculture, industry, and household), and how the model decides on the waste management is shown. Waste management technologies have been selected in the early years. The development of an industrial park means identifying regional potentials for the waste management market. Due to the priorities of reducing regional pollution, a large part of industrial assets is dedicated to the production of liquid fuel for the transportation sector, which requires for the ecotourism population. Compost generation has been selected as one of the sources of economic value-added production in the second stage. Energy generation from biomass has been selected for the power generation for the nexus of waste, water, and energy development in this model.

Industrial waste management, which mainly consists of fishery and ice-making processes. Because of the composition of fish meat, this kind of waste has a good potential for biodiesel production, which can be done through the anaerobic digestion process, transesterification pro-

Table 5
Mass balance in Lithosphere in the last year.

Materials	soil	load	Output (by agriculture products)	net
Nitrogen(ton/ha)	13.49	+1570	−248.580	+1334.9
Phosphorous(ton/ha)	5.1	+2623.16	−298.2	+2330.06
Potassium(ton/ha)	12.74	+4710.8	−2981.82	+1741.72
Ni concentration in soil (kg/ton)	0.08	+0.087		+0.006
Zn concentration in soil (kg/ton)	0.046	+10.74	…	+10.7
Cd concentration in soil (kg/ton)	0.0004	+128.71	…	+128.7

Accumulation (+)/ consumption (-).

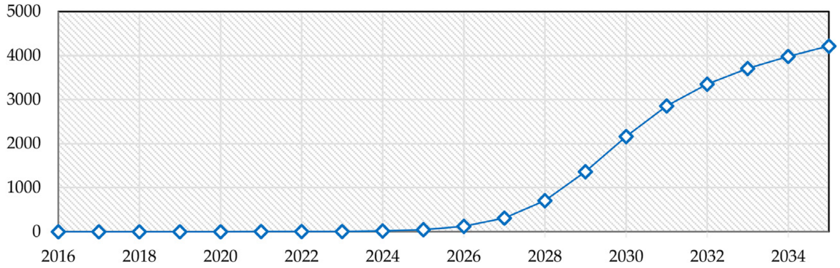

Fig. 8. Eco-industrial Park in zero municipal waste production (eco-tourism development) (ton/year).

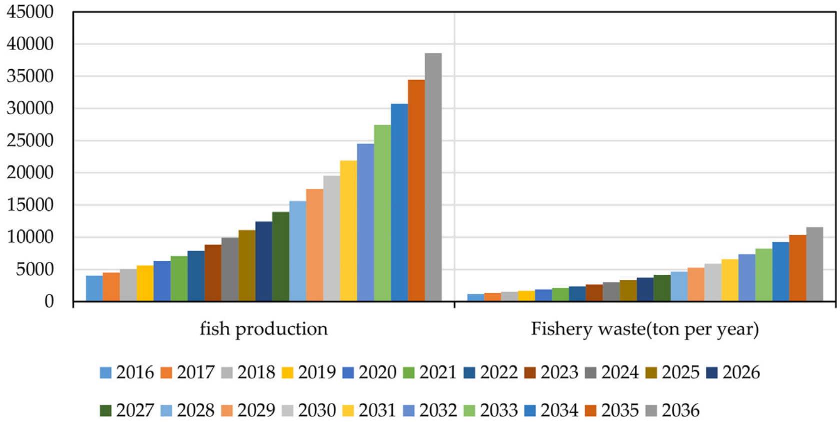

Fig. 9. Developing industrial activity (Fishery industry) and waste generation in the case study.

cess, and biodiesel production. For this reason, the construction of this unit and its capacity are defined as a decision variable. In this scenario, which has zero industrial waste to the environment as a constrain, all waste generated in the biodiesel production process should be used. Urban wastewater discharge is associated with social costs and affects the environmental impact index. In the main structure of the model, in order to wastewater management, the process of sanitary wastewater treatment has been considered (active sludge technology). Wastewater treatment units are added to the undrinkable water and are used for irrigation and household consumption.

Soil- waste nexus development in the regional level

One of the most important uses of agricultural waste is related to agricultural fertilizer generation. Moreover, the management of effluents from the domestic sector produces is a considerable valuable waste for agricultural activities (qualified fertilizer)

Based on the number of available nutrients, and the crop growth rate, the amount of fertilizer and compost are calculated (Fig. 11). Due to the low cost of compost and decreasing the environmental effects, composting would be better than fertilizer.

Waste management and value-added in the regional level

As shown in Fig. 12, It hasn't been having a considerable effect on the value-added changes in the waste management process. Waste management processes lead to generating the high valuable by-products. Rubber and plastics are valued at about $ 250 per ton and fertilizer costs fluctuate from 120 $ to 240 $ per ton. Waste management, along with the effects of emissions reductions, can largely offset the technology costs in the early years of investment.

Eco-Efficiency: system and ecosystem development

It is clear that the increased population in the ecotourism development scenario has little differentiation with rural population growth. Because the value-added of ecotourism development is very low. As expected, the highest value-added is related to the fishery process unit, and other sectors have a small percentage of the total value-added. Moreover, Fig. 13 shows the variation of income, Cost, and Value-added over time.

Life cycle analysis has been considered in the context of environmental management. In this regard, the Eco-indicator 99 has been rec-

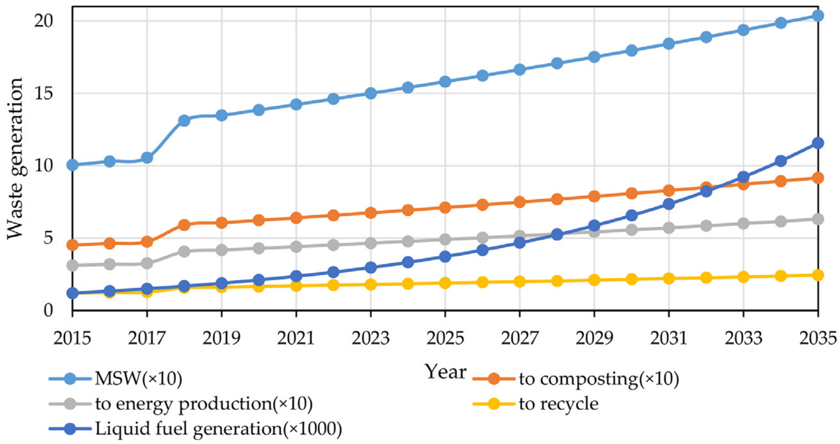

Fig. 10. waste management strategy in the case study.

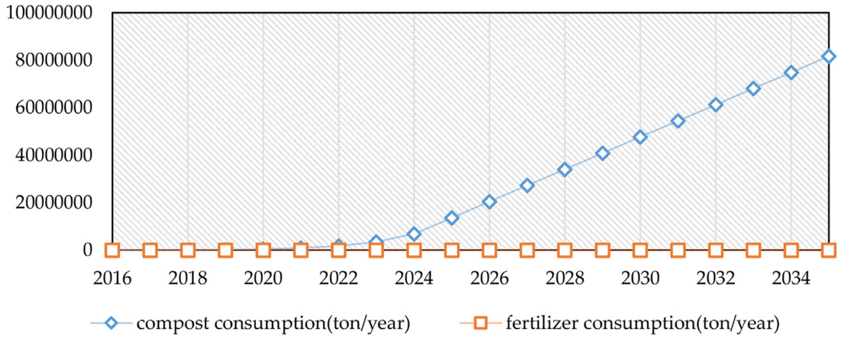

Fig. 11. The demand for fertilizer and compost in the soil.

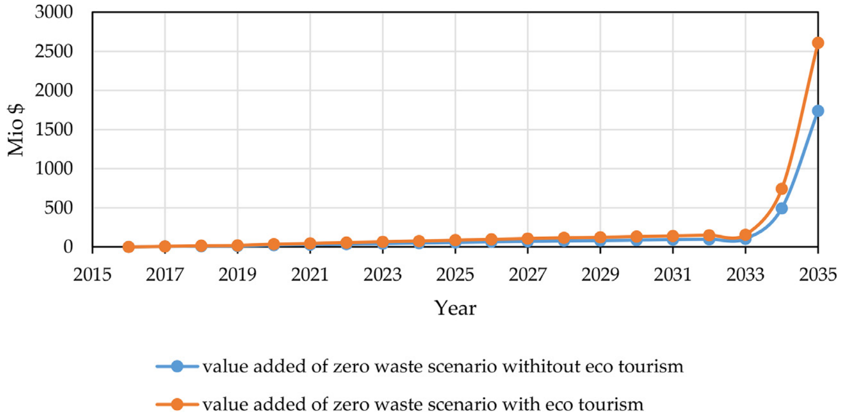

Fig. 12. Value-added generation in Eco-industrial park.

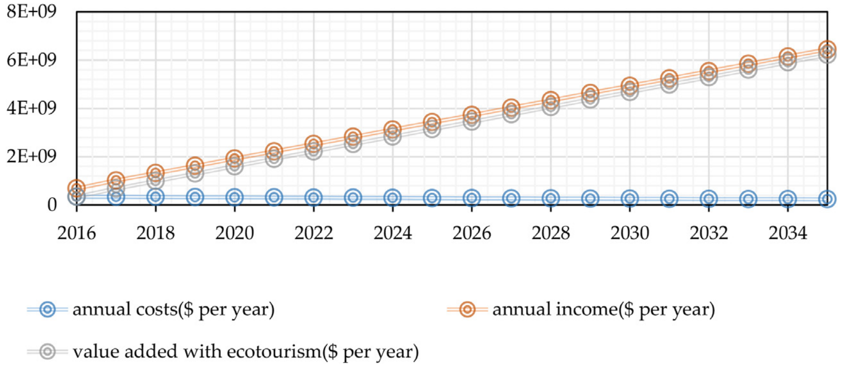

Fig. 13. The Chart of Income, Cost, and Value-added change over time.

ognized as a method for environmental impact assessment, and Eco-indicator 99 variation index is observed in the optimal time

Eco-efficiency is the objective function defined as the ratio of value-added to the environmental impact. In Figs. 14 and 15, eco-efficiency variations are observed during the time interval considered. The total value-added of the system is incremental and linear, and Eco-indicator 99 values decrease in the first years and then move to a constant amount (zero). By 2025, the Eco-indicator 99 index has a significant value, and the value-added is not very high due to the investment costs required to develop different infrastructures, the eco-efficiency is negligible and close to zero. From 2025 onward, the Eco-indicator 99 index converges to a steady amount, and value-added has significant growth, then eco-efficiency increases. This trend continues until the final year. In this regard, waste management technologies will be selected from the first year up to 2018, water desalination technologies and other sustainable ecosystem development technologies will be developed based on technology capacity growth by 2025. The agriculture supply chain will be developed from 2025 to 2030. In general, If Eco-tourism development

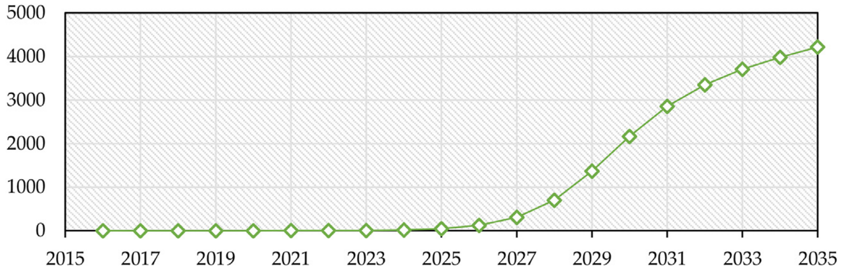

Fig. 14. Eco-efficiency variation during the time interval.

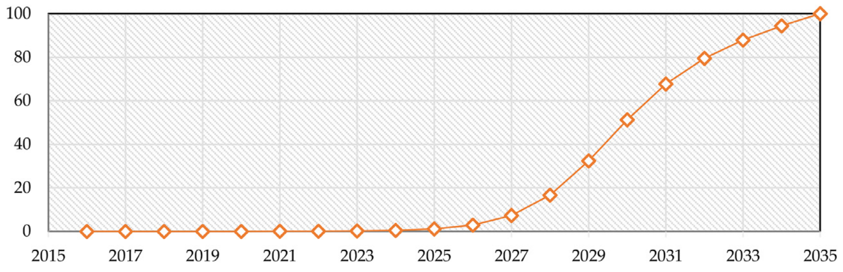

Fig. 15. The Eco-efficiency Score (%) in Shif Island.

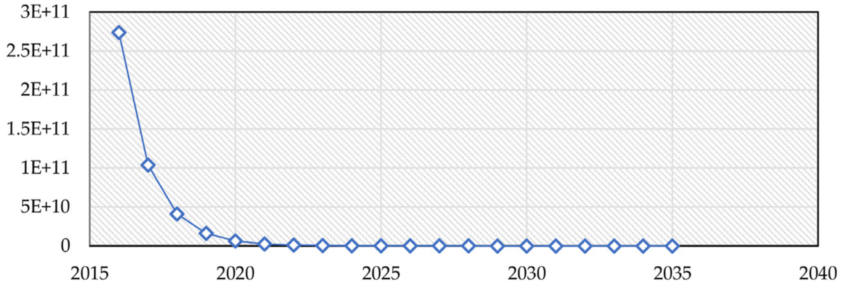

Fig. 16. Eco-indicator 99 index variation in the optimum model over time.

is not required (less than 1% of total value-added in last year), it can be neglected. In the following figures, the percentage of eco-efficiency is observed over a specific period. By 2025, the percentage of the eco-efficiency range is negligible at zero, and then it will increase at a considerable growth rate. By 2030, when sustainable development technologies have been developed, 50% of the optimal conditions have been achieved. By 2031, due to the agricultural supply chain, it will reach 70% percent, and finally, in 2035, it is in the optimal mode.

As shown in Fig. 16, developing waste management technologies in the first year, the Eco-indicator 99 index declines at a high annual rate. By 2025, all of the waste management technologies are developed in Shif Island, so the Environmental Impact Assessment Index has been modest, and moved to close to zero.

Sensitivity analysis and validation of the model

The validation of these types of models is very limited. Since the accessibility of ecosystem laboratory information is limited, therefore, in this research, all parts of the model have been validated seperately. In the water-food-energy sector, it has been used the sensitivity analysis on the main parameters(fertilizer and water price, and electricity tariff) . In the soil-agriculture model, this model has been validated by using the available data in the Lue paper [38,39] to check the applicability of the soil sector.

Sensitivity analysis of the model based on fertilizer price

Regional studies on the changes in fertilizer prices have shown that this parameter changes regionally and seasonally, and changes in this parameter have many effects on the choice of technologies. Hence, in this study, the sensitivity of the model is investigated based on the variety of fertilizer prices.

As shown in Fig. 17, by changing the price of fertilizer from 1 cent/kg in the first case, to 4 cents/kg in the third case, the model has shown great sensitivity to this parameter. At a price of 1 Toman per kilogram, the model has all the choices related to fertilizer needed to feed the land to purchase fertilizer, and compost fertilizer production technology is not a priority for the model. With the increase in fertilizer price, the model has shown a lot of sensitivity and at the price of 2 and 4 cents/kg, respectively, has reduced the share of purchased fertilizer from the market and has given priority to compost fertilizer production technology (Fig. 17).

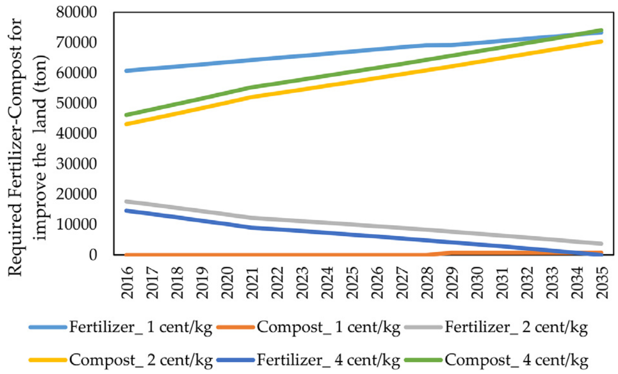

Fig. 17. Sensitivity analysis of the model based on fertilizer price(with eco-tourism development).

Sensitivity analysis of the model based on electricity tariff

One of the main parameters in determining the optimal technology for electricity generation is electricity tariffs. Considering the electricity tariff changes from 2.5 cents/kWh to 10 cents/kWh, the changes in the technology selection ratio are shown in Table 6. Given that the electricity tariff of the network affects the share of different electricity power generation, therefore, initially, a large percentage of electricity has been generated from the network. With the increase in electricity tariffs, the share of CHP technology, then solar electricity, and other technologies has increased. Given the cost of energy generation for a variety of technologies, which are CHP, solar, waste management, and tidal power, respectively, the model has behaved quite correctly in the choice of technologies.

Table 6
Sensitivity analysis of the model based on electricity tariff (with ecotourism development).

Technology	2.5 cents/kWh	6 cents/kWh	10 cents/kWh
PV	16%	9%	8%
CHP	20%	13%	4%
Tidal technology	4%	4%	4%
Waste to energy	12%	6%	4%
Grid	48%	68%	80%

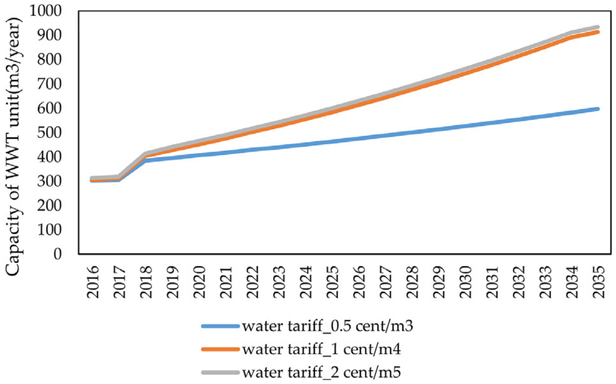

Fig. 18. Sensitivity analysis and validation of the model based on water price, and water (with ecotourism development).

Sensitivity analysis of the model based on water price

One of the sensitive parameters of the model is the water tariff, which affects the selected capacity of various wastewater treatment technologies. In this regard, the sensitivity of the model to changes in water prices and its effect on changes in the capacity of wastewater treatment systems have been investigated. As shown in Fig. 53, changes in water tariff have significant effects on changes in the selected capacity of the model. By increasing the price of water purchased from the network, the model has significantly increased the capacity of the wastewater treatment system (Fig. 18).

Validation of soil carbon (SOM) model

In order to validate the soil organic phase model, this study uses the predicted and experimental data which Luo used in his papers [38,39]. The output of the SOM prediction model, which contains the concentration of different pools in the soil, is calculated. The predicted trend of the SOM model is shown in Fig. 19.

By comparing the output of this paper and Luo paper, the error rate varies from 0.3% to 8.5%, and the average error is 4.4%.

Validation of nitrogen-phosphorus model

In order to validate the nitrogen and phosphorus competition model, the error rates of model output and actual data(Nutrient competition data in Tapajos National Forest [61]) are considered. The error rate of nitrogen and phosphorous competition is 17% and 1.4% error rate, respectively (Figs. 20 and 21).

Conclusions

Since we are witnessing inevitable resource scarcity in most civilized regions, the Water-Energy-Food-Ecosystem Nexus (WEFE Nexus) approach highlights the interdependence of water, energy, and food security and ecosystems – water, soil, and land – and identifies mutually beneficial responses based on understanding the synergies between water, energy and agriculture policies. On the other hand, according to the regional potential according to the type of ecosystem, the WEFE Nexus approach can use specific solutions based on different levels of interventions to achieve long-term economic, environmental, and social goals.

In this research, an integrated model of regional sustainable development has been proposed in order to reduce the consumption of materials and energy directly and indirectly, along with concerning the importance of economic development in a rural area. Regional planning includes forecasting the amount of nutrients (estimation of soil organic composition followed by estimation of phosphorus, nitrogen, and potassium), waste management in line with the development of the eco-industrial area, development of natural resources (mangrove forests) using the control of depletion of natural resources (biomass production), development of sustainable agricultural chain (analysis of nutrient limitation based on Liebig's law) and restoration of waste streams in order to manage the resources. This model has been developed considering demand (in two scenarios: with and without sustainable tourism development) and supply chains in the ecosystem and human works. Due to the review of re-use regenerators and regenerative recoveries in the model, it has been possible to develop a hybrid technology to consider

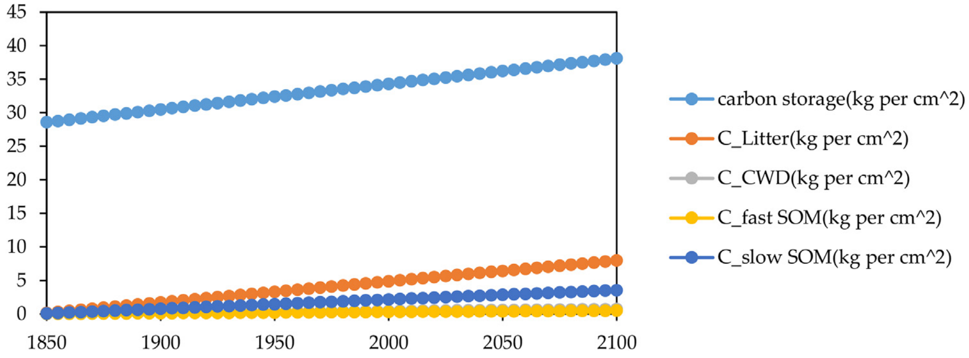

Fig. 19. The predicted trend of SOM model using Luo paper carbon canopy.

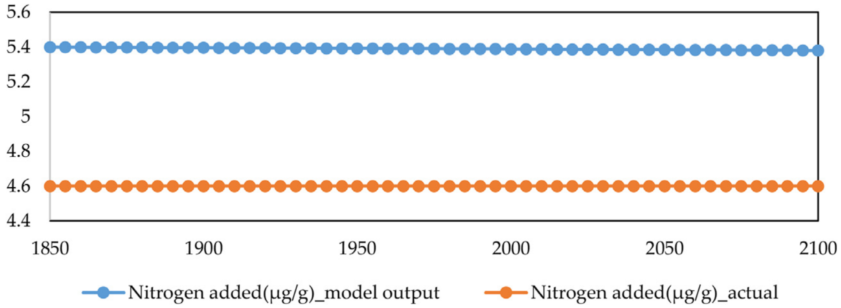

Fig. 20. Validation of nutrient competition data in Tapajos National Forest (Nitrogen).

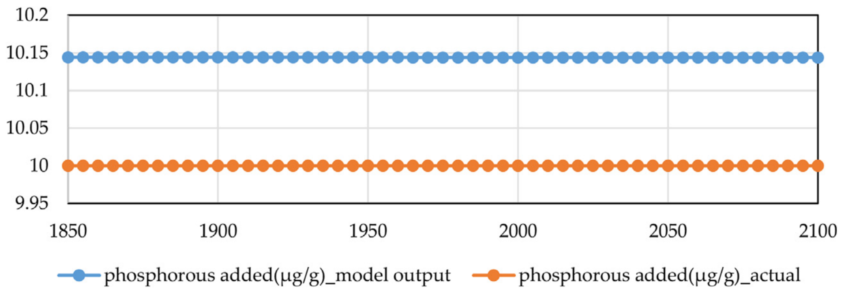

Fig. 21. Validation of nutrient competition data in Tapajos National Forest (Phosphorous) [30].

the cost of changing the effects of breakthroughs on the regeneration of the ecosystem. In this model, the producers of materials and energy are the main inputs of the ecosystem, and the outputs of the ecosystem include the outputs of the agriculture, forestry, animal husbandry, and fishing in remote areas, as well as mineral resources (industrial raw materials and fossil resources), solar energy and geothermal energy and other cases.

In general, in this paper, the symbiosis between living and non-living parts in the ecosystem has been developed in terms of the hybrid technology development to minimize the dynamic cost of changes, which can be suggested as the way to restore the ecosystem by considering the development and finally reached an optimal path for the development of living and non-living systems.

The use of optimization models in the management of water, energy, and food resources in nexus consideration, provides suitable options for political decision-makers, managers, and planners of these three sectors to preserve existing resources and achieve sustainable development, and pursue new climate water and earth energy analyzes to meet regional, national or global challenges and possibilities. In this regard, the developed model in this paper has comprehensive various aspects.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

The data that has been used is confidential.

Appendix A

Table A-1 has presented the main parameters of the FOREMAN model.

Table A-1
The main parameters of FOREMAN model.

Parameters	Item	Value
b2	Constant in height	48.04
DH	D multiply in H	1.4 × 35
D	The diameter of the crop (cm)	1.4
H_{max}	Maximum height(cm)	35
GD	Growth constant	162
$DEGD_{min}$	Minimum growth degree days	25
DEGD	growth degree days	36
C_1	constant	−0.5
C_2	constant	2.88
C_3	constant	−1.66
r_{AL}(light availability)	Light availability index	1
d	Constant for salt on growth	−0.18
$Salt_{05}$(salinity factor at $S = 0.5$)	Maximum number of sapling recruits per plot per year	100

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