

Review

Food System and Water–Energy–Biodiversity Nexus in Nepal: A Review

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Abstract: Water, energy, and biodiversity are essential components for building a sustainable food system in a developing country like Nepal. Green Revolution technologies and the package of practices largely ignored the role of ecosystem services, leaving a large population of small farmers' food- and nutrition-insecure. Biodiversity, especially, agrobiodiversity is in decline and this vital cross-cutting element is less discussed and interlinked in nexus literature. The interlinking food system with water–energy–biodiversity nexus, therefore, is essential to achieve a resilient food system. It ensures the vital structures and functions of the ecosystem on which it is dependent are well protected in the face of increasing socio-economic and climatic stress. This paper reviews the food system of Nepal through the lens of the food–water–energy–biodiversity (FWEB) nexus to develop a more robust food system framework. From this approach, food system foresight can benefit from different nature-based solutions such as agro-ecosystem-based adaptation and mitigation and climate-resilient agro-ecological production system. We found that the FWEB nexus-based approach is more relevant in the context of Nepal where food and nutrition insecurity prevails among almost half of the population. Improvement in the food system requires the building of synergy and complementary among the components of FWEB nexus. Hence, we proposed a modified framework of food system foresight for developing resilience in a food system, which can be achieved with an integrated and resilient nexus that gives more emphasis to agro-ecological system-based solutions to make the food system more climate resilient. This framework can be useful in addressing the Sustainable Development Goals (SDGs) numbers 1, 2, 3, 6, 13, and 15 and can also be used as a tool for food system planning based on a broader nexus.

Keywords: biodiversity; energy; food system; agro-ecological system; nexus; water

1. Introduction

A food system enabled with a large amount of agronomical research in the past led to an almost three-folds increase in productivity of major cereals, coarse grains, root crops, livestock, and fisheries to feed the growing population [1–3]. These achievements in advancement of food production, however, had been made possible at large environmental costs that resulted in loss of biodiversity and agro-biodiversity and depletion of essential natural resources such as water, land, and native agriculture gene pools including their wild relatives in nature [1,4,5]. Today about 820 million people are suffering from hunger and malnutrition deficiency [6]. The rising population will reach 9 billion in the next three decades, putting additional pressure on these resources [7]. The scarcity of natural resources necessary to produce additional food will lead to a rise in world food prices, consequences

of which may leave a significant amount of the population undernourished [8]. The disparity in food security is seen present today, like Sub-Saharan Africa and South Asia, which are severely affected by hunger problems compared to the other regions and post-COVID-19 situation looks even bleaker [9]. The Global Hunger Index 2019 for South Asia and Africa South of the Sahara shows a higher proportion of population undernourished as well as high prevalence of stunting and wasting among children [10]. A South Asian country, Nepal ranks at 79th position among 113 countries on food security index and has been struggling with food insecurity for a long time [11]. Since food security is the outcome of a food system [12], this factor points to a need for interdisciplinary thinking on food system planning as already postulated in recent Global Environmental Change reports and Food System concept [13,14]. Simpson and Jewitt [15] highlighted the importance of resource security to gain sustainability in all the four dimensions of food security, i.e., food availability, accessibility, utilization, and stability in a situation of vast growing population and climate change.

Water–energy–food nexus, an integrated solution to sustainable development, was proposed during the Bonn conference in 2011, emphasized the interconnection and interdependencies among the resources [16]. Today, the concept has gained attention of international agencies not only because of its holistic approach to resource utilization but because the modern world is also facing the challenges of climate change impacts on water, energy, and food resources [17]. Nexus is considered highly effective in managing natural and modified resources like land, water, energy, and biodiversity, thereby supporting developing countries to reduce risk of disasters and adapt to and mitigate the impact of climate change [18,19]. Recently, the International Union for Conservation of Nature (IUCN) has released global standards for nature-based solutions, which, among other things, highlights ecosystem-based adaptation [20].

Nepal, a mountainous country, has been facing the impacts of climate change in various sectors including, agriculture, forestry, livestock, health, and livelihood [21]. The country has witnessed a rise in mean annual temperature by 0.06 °C with an increase in maximum temperature, warm nights, and erratic rainfall pattern [22–24], which is predicted to be observed until the end of this century [21]. Bhattacharjee et al. [25] reported that the Himalayan regions and surroundings in Nepal are more vulnerable to climate change, which also makes vulnerable the livelihood of tens of millions of people who rely on its ecosystem services. The impact of climate change in water availability is predicted to impact multiple sectors such as the access of people to drinking water, irrigation during dry periods for agriculture production, and electricity generation [26]. To reduce vulnerability and increase resilience to climate change, the government of Nepal has prepared a climate change policy [27].

A sustainable and more holistic approach becomes essential to address growing water, energy, and food demand that is also environmentally sound. Such an integrated system should be possible by applying food–water–energy–biodiversity (FWEB) nexus that can link together the vital food system sectors, especially food production, surface and groundwater-based irrigation, hydropower-based energy, and natural biodiversity in an integrated and embedded system framework wherein these sectors interact positively by creating synergy and minimizing trade-offs among each other. This system of thinking and adaptive management of nexus has as its main objective to optimize the use of resources while simultaneously addressing inequity and conflicts as production grows much better in small and marginal farms that are more dependent on nature for nutrition and food [28,29].

This paper explores Nepal's current and future food systems through the lens of water–energy–biodiversity nexus, wherein the use of inland and groundwater and hydropower energy as ecosystem services supports the goal of achieving resilient and sustainable food system development by ensuring that both ecosystem structures and functions are managed to ensure sustained supply ecosystem services including water, energy, and food production. Additionally, adaptation to the climate and socio-economic changes are both considered equally important to strengthen the functioning of FWEB nexus [18,19,30]. The paper broadly discusses the prevailing food system of Nepal from the perspective of water–energy–biodiversity nexus.

The overall objective of the paper was to propose a modified food system framework that can be suitable to the context of developing countries like Nepal where livelihood is dependent on agriculture and natural resources. The specific objectives of the paper were (1) to understand the food system of Nepal, (2) to discuss various water scarcity conditions from FWEB perspective and the trade-off between irrigation and hydropower sector for water use, (3) to present solutions to water security from the FWEB perspective, and (4) to provide possible solutions to prevailing challenges in the agriculture sector.

2. Methodology

The methodology included the latest review of available literature on food system and food–water–energy (FWE) nexus together with the latest findings on the state of biodiversity in the world and the Asia Pacific region. Regarding the situation of Nepal's food system, we assessed the findings of several relevant papers on the Nepalese food system and various grey literature, discussion papers, workshop proceedings, and authors' insight and their experiences in the sector. Literature on climate change impacts was also reviewed in global and the country-specific contexts. This review included the publications related to biodiversity of Nepal, impact of climate change on biodiversity, and biodiversity as a component of nexus. A case study, associated with FWEB nexus, was also included in the review.

3. Understanding the Food System in Nepal

Geographically, Nepal is a landlocked country in the Hindu-Kush Himalayan region. However, it is well known for its richness of natural resources and biodiversity [31]. Nepal also contains a great diversity of food value plant species ($n = 790$) and forage species ($n = 577$) grown in the major three agro-ecological zones, namely, high hill (>2000 meter above sea level or masl), mid hill (1000–2000 masl), and Terai (69–1000 masl) [32]. The economy of Nepal is struggling to graduate the country from least-developed to a developing one but has failed to gain the desired growth rate. For example, it lags in per capita income and other indicators among the regional countries [33]. Agriculture contributes about a third of the country's gross domestic product (GDP) and employs about two-thirds of the population, primarily dominated by women's participation [34]. However, more than half of the households (52%) in Nepal are still food-insecure and 10% of them are severely food-insecure [35].

Nepalese agriculture is dominated by smallholders who occupy less than 0.5 ha land and have limited access to basic inputs like irrigation [36]. Land fragmentation has been one of the major bottlenecks for agriculture development due to high cost in production in lack of mechanization, which is often difficult in small parcels. Most of the farming is subsistence, grown in small plots, while very few are emerging as commercial or have adopted modern technologies. Most of them are confined to market areas with road access [37]. Farmers rely mostly on traditional knowledge and practice low-input agriculture systems such as farmyard manure, mulching, crop rotation, legume, etc., for soil, water, weed, and insect-pest management [38]. Besides, agriculture production is also constrained due to land degradation. According to IUCN [39], almost all types of land degradation exist in Nepal; among them, soil erosion, landslides, and flooding are the major types that contribute to land degradation processes. Human interventions due to increasing rural poverty are related to cultivation of marginal lands, excessive livestock grazing, and loss of biomass, resulting in continued land degradation. Most of the marginal agricultural practices have been carried out on sloping, fragile, mountain ecosystems without adopting proper conservation measures. There are both direct and indirect drivers that are contributing to land degradation in Nepal. Also, there exist some economic drivers that are directly and indirectly associated with degradation of agricultural lands, degradation of forest lands, and degradation of watershed areas, and other factors responsible for water stress, landslides, and flash floods, such as introduction of invasive alien species, etc. [39]. Similarly, haphazard urbanization and infrastructure development, rapid expansion of riverbed/conversion of fertile land, and climate change are also responsible factors for land degradation [39].

Cereals dominate other crops in Nepal, with a 49.4% share in agriculture GDP [40]. Rice (also known as paddy) is a principal crop among other major cereals because of its area of cultivation and yield (Figure 1). It shares 42.5% in total cereal cropped area, 51.6% in cereal food production, and contributes 20% in agriculture GDP. Maize, wheat, millet, barley, and buckwheat are other cereal crops grown mostly in rainfed conditions and in the mid-hill regions where irrigation development is lower [41,42]. Cereal production in Nepal is among the lowest in South Asia [40]. It has a lower yield than Bhutan, India, and other South Asian countries except for Afghanistan and Maldives [43]. Production of food crops is mainly dependent on timely and adequate monsoons, as only one-third of cultivated land has assured irrigation facilities [44]. Therefore, Nepal has been a major importer of rice a staple food crop. Nepal imported 531,000 tons of rice, amounting to \$210 million in 2015 [45]. However, in the recent decade (2007–2018), the yield of major cereals has shown an increasing trend while the area of rice and wheat cultivation shows decreasing. In contrast, maize cultivation area has increased in recent days [46]. Adoption of improved and hybrid varieties and better inputs (chemical fertilizer and irrigation) and technical know-how among growers have contributed to increased production of cereals [47].

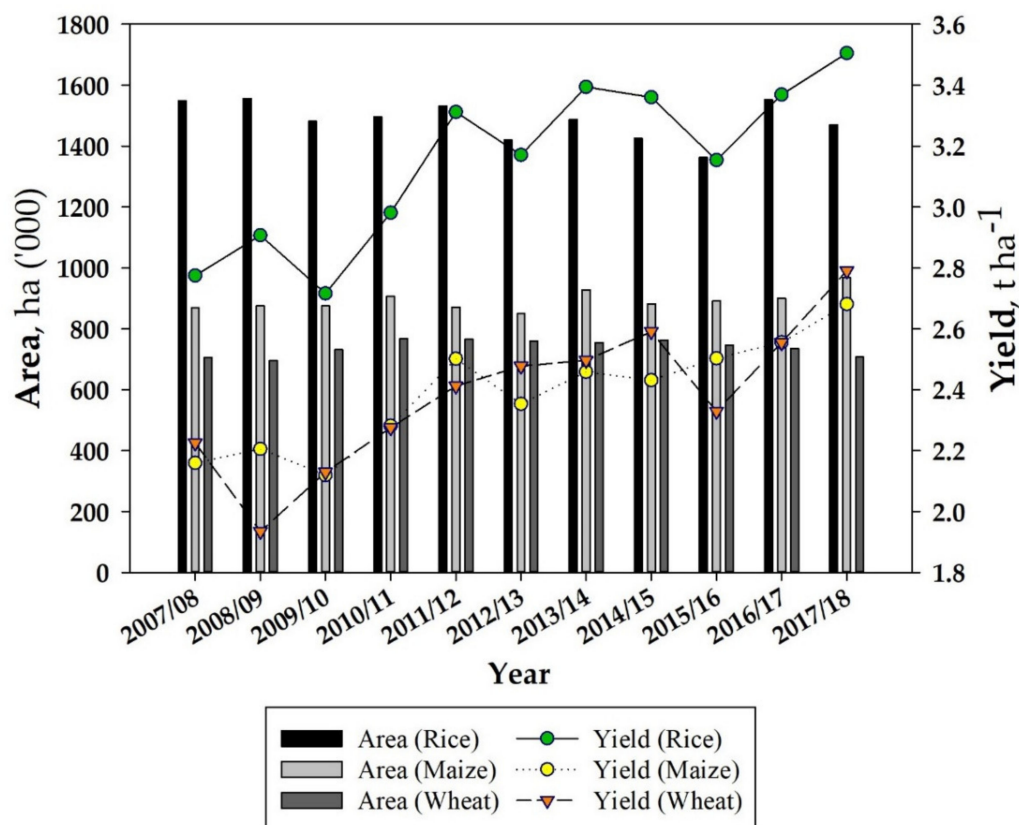


Figure 1. Trends of rice, maize, and wheat production and area covered in Nepal from 2007/08 to 2017/18.

On the other hand, food systems in Nepal have huge potentials to improve if opportunities bestowed by the rich bio-geographical and agro-ecological diversity are harnessed. Farmers grow large numbers of crops and rear livestock breeds. About 12 agro-ecosystems exist in Nepal that include 1026 species of crops and 35 livestock [48]. Besides crops, livestock is an important commodity in the food production system in Nepal and contributes about 26% in agriculture GDP [40]. Moreover, there are a large number of plant species such as buckwheat, millets, sorghum, soybean, etc., which are considered nutritionally important and underutilized species (NUS), are energy efficient, and can

withstand adverse environment condition for which they are recognized as future smart foods [49]. If these locally grown future smart foods are prioritized for production, there is ample opportunity to feed all those people isolated due to geographical remoteness [50]. The NUS has huge prospects to reduce food insecurity in the future; they are resilient to climate change and can grow in degraded land where main food crops are found unsuitable [51]. In Nepal, NUS is grown in marginal land, in low soil moisture regime, and slopes [32]. Table 1 shows NUS included in cropping season in various climatic regions of Nepal.

Table 1. Nutritionally important and underutilized species (NUS) include cropping systems in different climatic regions of Nepal.

Agro-Ecological Zone and NUS Cropping System	Climate	NUS Crops Included
Terai and Siwalik (<1500 masl) Maize+ Rice bean-Barley Rice-Barley Rice-Buckwheat Maize/Finger Millet-Fallow Maize/Finger Millet-Wheat	Sub-Tropical	Rice bean, Barley, Buckwheat, Finger Millet
Middle Mountain (800–2400 masl) Rice-Barley; Rice-Buckwheat; Maize-Barley; Finger Millet-Wheat	Warm and Cool temperate	Barley, Buckwheat, Finger Millet
High Mountain (>2400 masl) Rice-Barley; Maize-Oat-Finger millet (2 years); Potato+ Oat-Fallow (2 years); Rice-Fallow-Finger millet-Barley-Wheat (2 years); Potato-Fallow; Potato-Buckwheat; Maize-Rapeseed Oat-Fallow; Maize-Buckwheat	Cool temperate and Arctic	Oat, Finger millet, Barley Buckwheat

Source: Joshi et al. [32], Gadal et al. [52].

4. Water Security from Food–Water–Energy–Biodiversity Perspective

Nepal has an enormous amount of water and represents among the wealthiest countries in water resources [53]. Despite adequate availability of water, the country is ranked among the 44 countries having a high level of water stress [54], according to the definition of United Nations Water [55], mainly because of poor and non-inclusive access to good quantity and quality of drinking water and system vulnerability to mechanical, bacterial, and chemical pollutions. Naturally, the country endures variances in water availability; for example, there is a seasonal variation in precipitation. The country receives an average 1600 mm of rainfall annually in most of its region except in the Himalayan region, which gets rainfall less than 1000 mm [56]. About 80% of rainwater falls within four months, from June to September, while the rest of the year is almost dry. The country has more than 6000 rivers classified as perennial, semi-perennial, and seasonal, according to their origin. Koshi, Gandaki, Karnali, and Mahakali are four first-grade or perennial rivers that originate from snow glaciers and lakes. Rivers originating from the Mahabharat range or middle hills are called second-grade rivers, seasonal streams, or creeks (locally known as *Khahare*). The entire river systems yield around 225 billion cubic meters (BCM) of surface water annually. However, during the dry season the flow of large rivers is very low and many tributaries are almost dry.

Gyawali et al. [57] convincingly stated about water scarcity in Nepal. Vertical scarcity found in top-hill settlements, living almost 1000 m above rivers in fear of malaria, has been created in absence of any technological solutions, whereas in plains (Terai region) over-exploitation of groundwater within the country and transboundary region has created water scarcity due to inadequate water recharge. Furthermore, meteorological scarcity, caused by spatial variations from eastern to western regions and temporal variations of rainfall in different seasons, called hydrological scarcity, causes the higher flow during monsoon, i.e., about 225 billion cubic meter (BCM) for 100 days and lower flow during the remaining days, i.e., 30–35 BCM for 265 days. Groundwater scarcity caused by landslides or

human-induced pollution, agricultural scarcity, and the scarcity in agriculture production due to soil moisture and other agriculture factors affected due to nexus problems are among other forms of water scarcity in Nepal.

Water in Nepal has been underutilized. Only 15 BCM out of 225 BCM of water is utilized in the country [53]. This persists not because of surplus, but because of lack of appropriate distribution and management strategy. Water scarcity has impacted rural livelihood. The impact of water scarcity in mid hills, increased both due to drying up of the resources and unreliable water supply, has disproportionately affected women and girls of poor households [58]. While about 96% of water is utilized in the agriculture sector, the country has year-round irrigation in only one-third of its irrigated area [44].

Irrigation development in Nepal started in the 17th century. The Argheli irrigation project in Palpa district in the western mid hills is the oldest known irrigation canal constructed by King Mani Mukunda Sen. There are numerous other small-scale canals, called as “Raj Kulos”, that were constructed during 17th and 18th centuries. However, the first extensive public sector irrigation canal system was developed in 1922, renowned as “Chandra Canal System”, has a net command area of 10,000 ha, and is still in operation [59]. Irrigation systems of Nepal, according to management, can be categorized as an agency-managed irrigation system (AMIS), managed by the Department of Irrigation (DOI), and farmers-managed irrigation system (FMIS), managed by the Water Users’ Association (WUA) for its operation and maintenance. Similarly, the irrigation systems are also categorized as major, larger, medium, and small, according to the command area (Table 2).

Table 2. Irrigation systems, according to the command area in Nepal.

Irrigation System	Command Area (max-min)
Major Irrigation System	>500 ha—Terai; >100 ha—Hills
Larger Irrigation System	>2000—<5000 ha—Terai; >500—<1000 ha—Hills
Medium Irrigation System	>200—<2000 ha—Terai; >25—< 500 ha—Hills
Small Irrigation System	<200 ha—Terai; <25 ha—Hills

Source: Poudel and Sharma [60].

Farmers-managed irrigation system has been more successful in irrigation water management than AMIS in Nepal. Irrigation under FMIS covers about 167,925 ha agriculture land [44]. Because of its success, the Government of Nepal has prioritized FMIS in raising agricultural productivity. However, there is a need for continued improvement in institutional arrangements to make FMIS more inclusive by involving farmers, regardless of their residence at the head end or tail end part of irrigation canals [61,62]. The role of irrigation has always been more important in raising agricultural productivity than other inputs [63]. Figure 2 shows increased irrigation facilities raised the yield of major cereals by 9.4% in early paddy, about 50.1% in main season paddy, 75.5% in wheat during winter season, and 54.9% in maize from both agency-managed and farmers-managed irrigation systems [64].

There are various challenges in irrigation systems in Nepal. The current irrigation systems are poorly performing on efficiency. Canal capacity is underutilized, as is the participation of water users. Most of the irrigation schemes are developed from small rivers and tributaries rather than larger perennial rivers because of potential riparian effect [65]. Impact of climate change at Himalayan regions has increased threat of glacial lake outburst floods (GLOFs), which can cause potential disaster in downstream regions [54]. In a longer run, the speed melting of snow may decrease river flow and reduce available surface water [66]. Biodiversity loss due to anthropogenic causes or other causes of climate change can cause habitat loss, which can alter the freshwater system—an essential ecosystem services for drinking water and food production system [67]. This brings about the nexus approach of solution thinking to address multisector problems for human welfare.

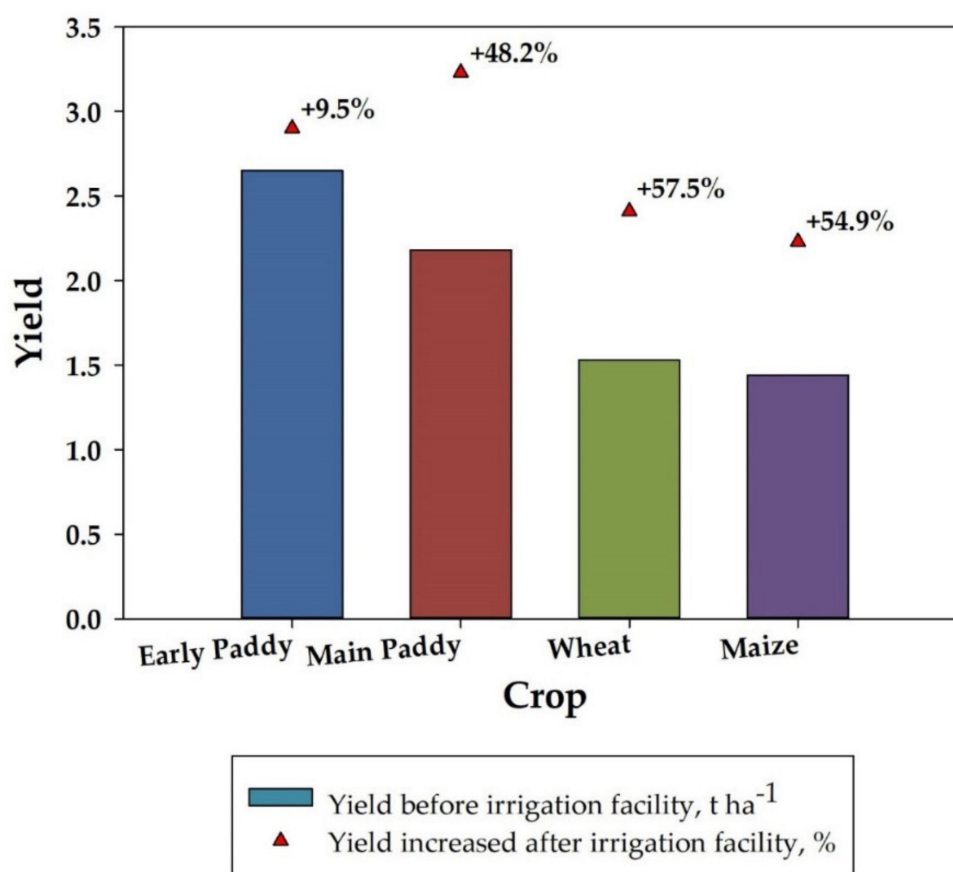


Figure 2. Yield of major cereals before and after irrigation facility through agency-managed irrigation system in Nepal.

Sustainable solutions for water security also require acknowledgment of local knowledge and practices of water use by communities in Nepal. Water management at the local level follows watershed boundaries that helps wise use of water resources for drinking, irrigation, and sanitation purposes. This also informs national policy to follow basin-wide management of water along with forest, watershed, and agricultural practices, thus distributing water allocation based on supply and local demand. This local and indigenous knowledge and adaptive methods help in designing and planning of irrigation and drinking water in an integrated manner as the structures are simple and maintenance on a collective action basis also adapts to climate change, altering cropping patterns more toward mixed cropping to make food production system more resilient in water use [68]. Various resilience measures are found in Nepal's hill farming systems to conserve water through conservation farming in a landscape-management approach. In the mountains, rainwater harvesting in ponds, rooftops, irrigation systems, field terraces, and dense vegetation is practiced at landscape level to store rain water, while at farm level various short-duration, stress-tolerant varieties are grown to escape or adapt to the changing climatic condition. Other measures include planting of multipurpose crops, including leguminous trees and shrubs as agroforestry trees, wind breaks, shades, and shelter to crops and livestock, and helping to retain soil moisture by regulating temperature of the micro-climate [69]. Similarly, NUS crops are extensively grown in Terai, hills, and mountains in Nepal. Some of the NUS crops belonging to cereals, pulses, fruits, vegetables, leafy vegetables, fruits, oilseeds, and spices for, e.g., sorghum (*Sorghum bicolor*), buckwheat (*Fagopyrum tataricum*), pearl millet (*Pennisetum glaucum*), rice bean (*Vigna umbellata*), horse gram (*Macrotyloma uniflorum*), etc., are grown, which are nutritionally rich in micro-nutrients [32]. These crops have additional advantages other than nutrition; the crops can

withstand drought condition, show resistance to heat, waterlogging, and salinity condition, and have higher water-use efficiency than major cereals [70].

Case Study: The Water Mills—Multiuse of Water

Water resources, for a long time, have been utilized for generating energy in Nepal. The rural water mill system in Nepal is one of its traditional examples [71]. The watermill utilizes the potential energy of water, converts it into kinetic energy by dropping water from some height that makes a water jet, which then turns the paddle, generating rotating energy (Figure 3). This rotating energy is used for grinding grains by attaching a grinding stone coupled at the top of rotating shaft. The improved design of the traditional watermill has better efficiency in grinding grains, hulls, rice, and can produce 3–5 KW of electricity. It has been estimated that about 30,000 traditional watermills are running in Nepal. However, the number tends to decrease due to urbanization and mechanization (e.g., introduction of diesel-powered machines). Water mills in Nepal have improved lives, reduced workload of women, and supported income generation activities of rural people. In addition to this, improved the water mill has been integrating the irrigation facility by sharing water mill canals for irrigation purpose, making it irrigation, agro-processing, and electricity generation services [72].

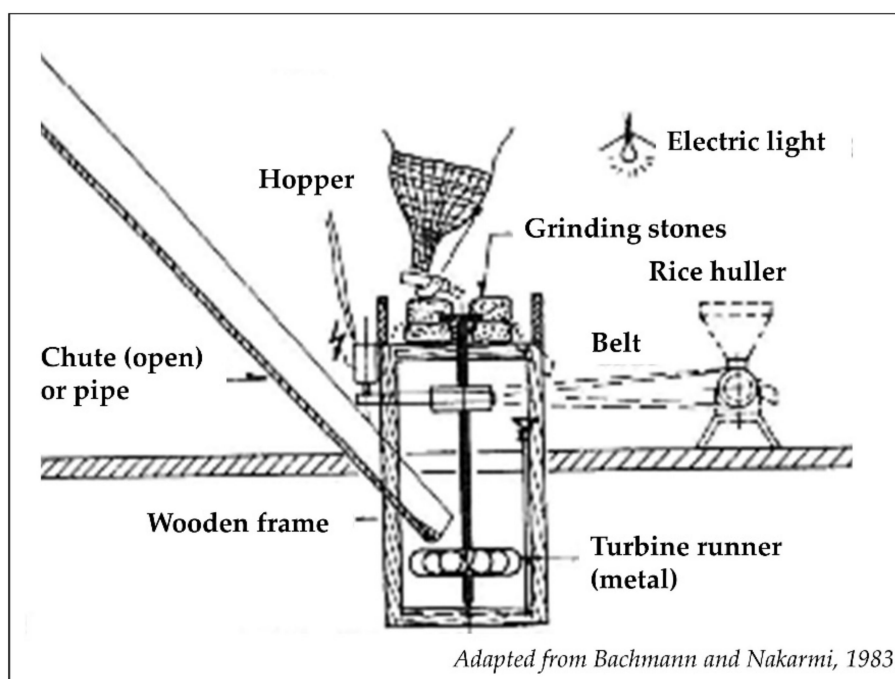


Figure 3. New Nepali water mills for improved grinding.

5. Trade-Off between Hydropower and Irrigation System in Nepal

Agriculture and hydropower are important economic sectors of Nepal. Agriculture is important as it involves about two-thirds of the population and contributes one-third in national economy. Hydropower is an important sector to fetch currency from massive water resources in the country. Nepal has 83,000 MW of potential in hydropower development of which a prospective 114 projects that can generate 45,610 MW have been identified to be economically and technically feasible [53]. Since 1991, Nepal has progressed tremendously in hydropower development. After policy reform in 1992 for private sector involvement in hydropower and subsequent introduction of community electrification policy in 2003, electricity production has expanded to rural parts of Nepal as well [57]. Most of the hydropower technology in Nepal is based on the run-of-river type, which is dependent on seasonal river flow [73].

Nepal receives a large volume of water from snow and glaciated areas that cover 3.6% of total land area. Nepal's river basins extend to 194,471 km² in the transboundary regions, of which 74% lie in Nepal. The country has 5000 natural lakes, 1380 reservoirs, 5183 traditionally built ponds, and groundwater with renewable potential [56]. These water resources are utilized for agriculture (95.9%), domestic purpose (3.8%), and industry (0.3%). In addition to 15 billion m³ of surface water use, an additional 8.8 billion m³ of water is withdrawn for agriculture and domestic purpose from shallow and deep groundwater aquifers [74].

The utilization of water for irrigation in agriculture and drinking water are given the highest priority and, thus, presents a potential trade-off for water use with other sectors. Water use in agriculture is prioritized because increased irrigation facilities along with other inputs and favorable monsoon weather showed a growth rate of 5.5.% in food production in 2019 [75]. Furthermore, Nepal's Agriculture Development Strategy (ADS) 2010–2030 has envisioned to increase crop productivity of major cereals in 20 years to transform from a food-deficit to food-surplus country [76]. Irrigation is also prioritized to decrease the fluctuation of yield due to erratic rainfall [77]. Meanwhile, demand for irrigation is also increasing due to increase in peri-urban agriculture that in recent days has boosted due to increased urban population [78]. Farmers have shifted from cereal-based agriculture to more input-intensive cash crops that have helped them to raise agriculture income [79]. However, it may lead to unsustainable water mining as the increased commercialization with high return possibility encourages farmers to invest in groundwater pumping [57].

The solution to this trade-off in water use can be the multipurpose water and energy management systems wherein river water is harnessed both for generating hydropower and used water is then canalized to irrigate agricultural land. Karmacharya [80] explains the envisioned irrigation expansion by the Government of Nepal can mutually benefit from the hydropower projects as it reduces costs to a large extent if a synergistic model is adapted. A good example is the Bheri-Babai diversion project, where water in dry season is diverted toward the agriculture land that will irrigate 40,000 ha in Banke and Bardiya districts at the same time the water is used to produce 45 MW of electricity. The supplemental economic benefits gained from electricity can be utilized for the maintenance and repair of irrigation canals [81]. The relationships between hydropower and irrigation schemes can thus be made complementary. The presented Table 3 enlists various trade-offs and complementary relationships between hydropower and irrigation projects in Nepal.

Table 3. Various relationships between hydropower and irrigation projects in Nepal.

Relationships	Projects
Only Hydropower	Tinau hydropower, Khudi hydropower, Pharping hydropower, Marsyangdi hydropower
Hydropower utilizing irrigation infrastructure	Bijaypur, Task, Phewa, Sunsari, Morang
Hydropower causing irrigation defunct	Trishuli Devghat
Irrigation system with in-built hydropower	Adhikhola irrigation, Bheri-Babai, Rani Jamara Kuleriya, Seti Irrigation System, Chaurjaha, Khopasi
Hydropower Trade-off with Existing Irrigation	Jhimruk, Puwa Khola, Mai Khola, Seti Reservoir System
Irrigation Supporting Hydropower	Jhakri Khola FMIS at Headwork supported hydropower for Khimti Hydropower

Source: Pradhan and Belbase [81].

6. Food System Linking with Water–Energy–Biodiversity Nexus

Food–water–energy–biodiversity systems are intimately connected and, among them, biodiversity provides various ecosystem services, a crucial component to make water–food–energy nexus work [19]. Healthy ecosystems, such as forest, grasslands, and wetlands, provide clean and adequate water to grow crops and produce energy. Without river catchments producing water in all seasons, energy to lift and store water is not possible, at least in the context of mountainous and hilly country Nepal [42]. Food, water, and energy are equally dependent upon each other, and biodiversity links and energizes them all. The connection among these systems is known as the FWEB nexus.

While the FWE nexus is well recognized and discussed in the international discourse on food and environment security, biodiversity is the unrecognized and undervalued fourth dimension of the nexus (most commonly seen in food–water–energy nexus literature) [16,82]. However, ecosystem services derived from biodiversity and ecosystem level underpin each of the three securities of FWE. Nature (most prominently expressed in terms of biodiversity) helps mediate the FWE nexus links by storing, moving, cleaning, and buffering flows of water, making drought and flood less severe and food and energy production more reliable [19]. Without healthy biodiversity and ecosystems in well-functioning watersheds, river catchments, basins, and mosaic landscapes, the infrastructure built for irrigation, hydropower, or municipal water supply may not function sustainably and is unlikely to ensure healthy food and nutrition security [83].

Similarly, unmanaged and unsustainably managed watersheds and water catchments will reduce the energy outputs generated by hydropower dams [84]. In a mountainous country like Nepal, nature's geological and geographical buffering role is critical to keep the FWEB nexus operational. Without a sustained flow of quality water and clean and affordable energy, food production cannot be maintained as per the demand and food security is impossible to assure. So, it is clear biodiversity and its extension nature is part of the resources or infrastructure needed to manage the FWEB nexus and ensure sustainability and resilience of critical livelihood components and human well-being agenda.

Understanding the role of nature in the nexus changes the picture of what investment is needed to ensure food, water, energy, and health security. In the food systems' research, the role of nature and ecosystem services should be the focus for policy, institutions, and governance reforms and investment priority for strengthening the nexus and for improving the food, water, energy, and human security. This will be possible through equitable and inclusive social, economic development and environment conservation. The failure of the conventional development model to push economic growth without ensuring the sustained supply of ecosystem services is now well accepted as not being a sustainable solution. Reframing the development or food security problem as the nexus framing alone will not change the fundamental folly of ignoring the integral role of nature's contributions in human well-being and good quality of life [14].

The above information has clearly shown the complementary and synergistic relationship among FWEB that can be harnessed to do local, subnational, and national food systems in Nepal. Food for maintenance of the human body, clean drinking water for health and sanitation, energy for cooking, lighting, cooling, and heating, and biodiversity as basic infrastructure to link them with each and among themselves are important components to human survival. The rising population with changing demographics and cultural characteristics is putting more demand on these components. Thus, there is a need to strengthen this nexus to ensure resilient food systems. We need to restructure institutions, markets, and governance to manage this nexus to achieve safe, healthy, inclusive and sustainable food systems that will help achieve sustainable development goals [85]. Nexus thinking is, thus, a system thinking approach that considers all the related components together rather than in isolation to maintain the appropriate balance among them [86].

7. Nexus Solution to the Food System Challenges in Nepal

Food–water–energy–biodiversity nexus has never been as important and urgent in Nepal than today. Nepal's population is projected to be 36.2 million in 2050 [87]. With one of the lowest per capita amounts of agricultural lands in the world, the food system scenarios in Nepal are challenging. According to a study conducted by Feed the Future program of the USAID [88], Nepal is a severely food-deficient country. Declining agricultural production has depressed rural economies and increased widespread hunger and urban migration in Nepal. This situation is compounded by a population growth rate of 1.8% per year and a high ratio of population to arable land. "The main underlying causes of hunger, poverty and under nutrition in Nepal include low agricultural productivity, limited livelihood opportunities, weak market linkages, and inadequate production and consumption of nutritious, locally-available foods" according to the USAID study. The economy of Nepal and the livelihoods of

its people are highly dependent on the monsoon weather and, therefore, high climate variability is likely to affect food systems adversely. A recent report assessing the possible impact of climate change on Nepal’s GDP found that the effects of climate change on water-induced disasters at the national level might cause additional average annual direct cost equivalent to 0.6–1.1% of current yearly GDP by mid-century with an upper estimate of almost 3% per year [89]. Damage to agriculture output is expected to be high.

The solutions to the current challenges of food system in Nepal can be found in an enormous amount of literature that provides nature-based solutions providing holistic management of nexus component. As stated by Rasul and Sharma [18], solutions to food system based on the silo approach may lead to negative consequences on the resources and can be maladaptation. The proposed modified nexus framework that integrates FWEB components recognizes the prime role of biodiversity as a naturally and human-modified infrastructure to enhance the supply of food, water, and energy that can be utilized and adaptively managed according to the local and national situation prevailing in Nepal (Figure 4).

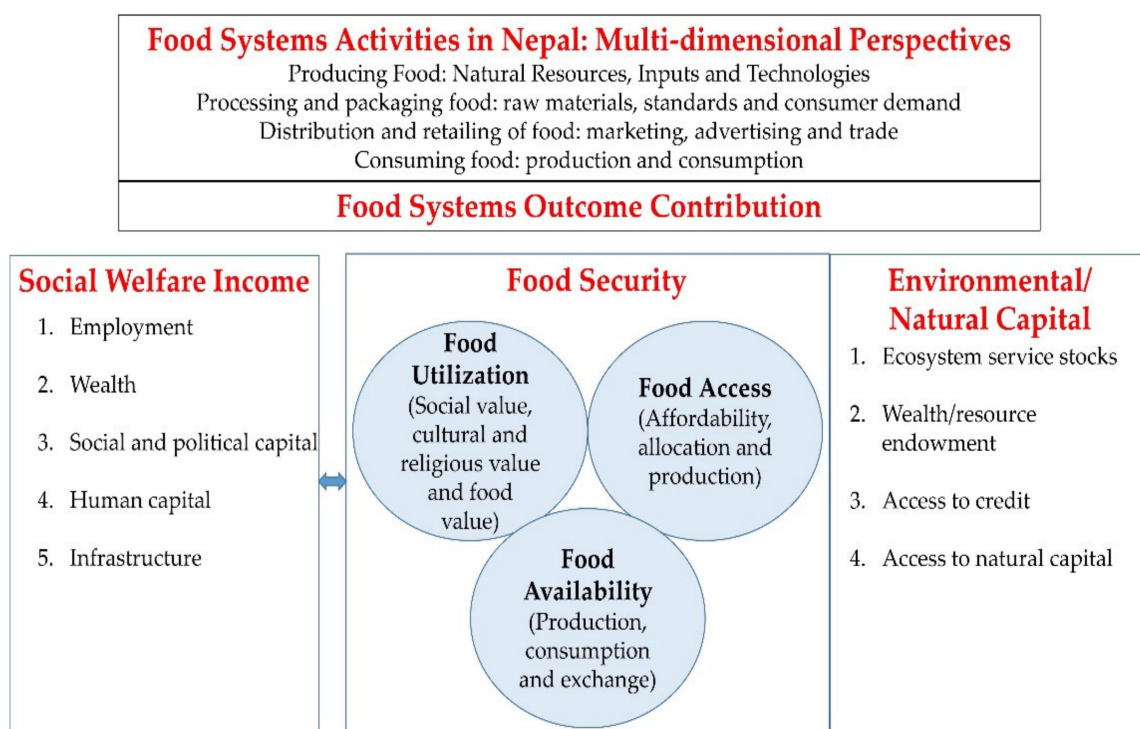


Figure 4. A modified nexus framework of food system in Nepal (adopted from Ericksen [12] as reported by Immaculate [90])

Karki et al. [91] presented 10 major challenges of the food system in Nepal (Table 4). These challenges are directly related to the components of food system, i.e., food production, processing, distribution, and consumption. The table shows that inadequate production of food caused due to low productivity, fragmented land holdings, and the subsistence nature of farming while land abandonment, changing food habits, high cost of production, weak climate resilience in agriculture, decreasing food diversity and poor collaboration among research, academics and extension institution are other challenges in food production. Geographical remoteness in production clusters, climatic shocks, problems in transportation, and lack of buffer stock cause difficulties of food distribution and processing. Similarly, challenges in food consumption are observed due to increased population pressure and traditional system of subsistence farming, changing habits to consume processed food, food damages due to climatic shocks, inflation in food, and lack of awareness among people on nutritional food consumption.

Table 4. Challenges of the food system in Nepal and the food–water–energy–biodiversity (FWEB) nexus solutions.

Challenges of Food System in Nepal	FWEB Nexus Solutions	Related FWEB Component
Low levels of production and productivity	Sustainable and inclusive intensification for e.g., Conservation agriculture, Breeding drought resistance varieties, Aerobic rice, [16];	Food-Water-Energy-Biodiversity
	Irrigation infrastructures, solar based irrigation, spring rejuvenation [42];	Water-Energy
Fragmented land holdings, land abandonment and scattered production	Farmers' innovation for e.g., straw mulching FYM use, researches on drought resistant varieties and digital agro-advisory services [56]	Food-Water-Energy
	Voluntary land consolidation program [92]	Food
	Incentives to high value agriculture production, agro-advisory services and infrastructure to make market [93]	Food
Subsistence farming and increased population pressure	Mechanism for cross-border food trade and food banks [93]	Food
	Sustainable and inclusive intensification for e.g., Conservation Agriculture [16]	Food-Water-Energy-Biodiversity
	Incentives to high value agriculture production, agro-advisory services and infrastructure to make market [93]	Food
	Cereals, vegetables and integrated aquaculture system [30]	Food-Water-Energy-Biodiversity
Changes in eating habits—increasing consumption of processed food	Promote water and energy efficient crops with low carbon footprint [94]	Food-Water-Energy
	Development of nutrient rich agriculture system considering human health and environment benefit [95]	Food-Water-Energy-Biodiversity
	Promotion of future smart foods: Sorghum, millets, legumes that can grow with low inputs and can withstand biotic and abiotic stress [50]	Food-Water-Biodiversity
Weak climate resilience, frequent climatic shocks and damages	Transforming food system with availability of year-round diverse and nutritionally rich foods [96]	Food-Biodiversity
	Adaptation measures to climate change considering nexus of food water and energy [18]	Food-Water-Energy-Biodiversity
	Diversified agro-ecological system [97]	Food-Water-Energy-Biodiversity
	Adoption of climate smart agriculture [98]	Food-Water-Energy-Biodiversity
High costs of production and soaring food prices	Reduce risk of climate change by mainstreaming climate action in food system [99]	Food-Water-Energy-Biodiversity
	Scale appropriate and socially and environmentally responsible agriculture mechanization [100]	Food-Energy-Biodiversity
Transportation and distribution problems	Mechanism for cross-border food trade and food banks [93]	Food
	Improved connection between local and regional market and improvement of roads and bridges [101]	Food
	Investment in warehouse, transport facility or aggregation centers [102]	Food
Inadequate food buffer stocks & poor distribution system	Improved connection between local and regional market and improvement of roads and bridges [101]	Food
	Investment in warehouse, transport facility or aggregation centers [102]	Food
Decreasing food diversity; low awareness on the need to address food and nutrition security	Development of nutrient rich agriculture system that considers human health and environment benefits [95]	Food-Water-Energy-Biodiversity
	Promotion of future smart foods: Sorghum, millets, legumes that can grow with low inputs and can withstand biotic and abiotic stress [50]	Food-Water-Energy-Biodiversity
	Transform food system with availability of year-round diverse and nutritionally rich foods [96]	Food-Water-Energy-Biodiversity
Poor collaboration and cooperation between research, academia and extension	Strengthen the pluralistic agri-extension system [103]	Food-Water-Energy-Biodiversity

Most of the challenges stated in Table 4 indicate that the food system Nepal is facing are mainly related to low production and productivity. Sustainable and inclusive intensification and an innovative and sustainable farming system approach can increase agriculture production by improving the system efficiency, which also includes synergizing opportunities for poor farmers who traditionally rely on ecosystem services for their livelihood [16]. The water resource challenges can be addressed through investing in irrigation infrastructure. Investing in solar-based groundwater irrigation systems that will allow post-monsoon cultivation in Terai region can foster productivity while breeding drought-tolerant varieties, such as *Sukhadhan* of rice for drought and *Suwarna-Sub* for flood-prone areas [57]. However, conservation of water resources should be prioritized to rejuvenate spring sources by various means of water-conserving technologies, such as digging water-recharge ponds at hilltops [42].

Transformation of subsistence agriculture to commercial, large-scale farming requires land consolidation, which also reduces the risk of fragmented land being used for non-agriculture purpose [104]. Volunteer mechanisms for land consolidation can be nonconflicting measure [92] that, once implemented, will open an avenue for agriculture mechanization that is scale appropriate

and socially and environmentally responsible [96]. Incentivizing in high-value agriculture production enabled with sound agro-advisory services and investing in marketing of products [93] can increase return from agriculture. Similarly, for landlocked mountainous countries like Nepal, combinations of cereals, vegetables, and integrated aquaculture systems can be one of the beneficial FWEB solutions to the agriculture system [30].

Food system in recent days needs to be transformed from a more energy-content diet to a balanced and nutritious diet. Biodiversity in agriculture can make year-round availability of nutrition-rich foods [96] and Nepal needs to promote nutritionally rich and underutilized crops found abundantly in the country [50]. Agriculture system that produces nutrient-rich food and considers human health can benefit the food system [95]. Nexus-based solutions are also acknowledged for their effectiveness in adaptation to climate change [18]. A complete paradigm shift in food system is envisioned through a diversified and agro-ecological system that addresses the issues of subsistence farming as well as industrial agriculture [94]. The promotion of technologies that reduce carbon footprint in agriculture can efficiently produce crops [89]. Adaptation to climate change is a priority of the government of Nepal. In the agriculture sector, climate-smart villages, climate-smart agriculture, and conservation agriculture system and innovation (CASI) models have been tested and proposed [98,105]. However, strategies for adaptation are limited to an agriculture sector-based approach. Yet, climate risk can be minimized by mainstreaming climate action in agriculture [99]. The food system to be resilient requires a sound and efficient food distribution system. Shively and Thapa [101] correlated food prices with roads and bridges in Nepal and suggested the regional and local markets need to be connected. Hence, food system resilience can only be assured when the investment in warehouse, transport facility, or aggregation centers is prioritized in geographically isolated areas [102].

8. Conclusions

A proper and dynamic understanding of the role of biodiversity in the traditional food–water–energy nexus changes the scope of what research, extension, and investment interventions are needed to ensure water, food, and health security or a resilient food system in Nepal. Nature and ecosystem services should be the focus of policy, institutions, and governance reforms in agriculture transformation in Nepal. Updating investment priority based on this broader nexus can help Nepalese policymakers to abandon a silo approach in agriculture plans and seek solution in water, forestry, and energy sectors to achieve the cherished goal of food and nutrition security through equitable and inclusive social means, economic development, and environment conservation. The failure of the conventional agriculture development model to push economic growth without ensuring the sustained supply of ecosystem goods and services is now well accepted. Reframing the food security problem and using foresight thinking with this broader nexus framing of the food system paradigm may change the fundamental folly of ignoring the integral role of nature's contributions in food and nutrition security in developing countries. The modified nexus framework for assessment of the food system in Nepal is based on this more integrated and resilient nexus approach that adds nature to energize the food–water–energy system sustainably. This broader and holistic thinking is highly relevant in addressing the intractable challenges Nepal faces to achieve Sustainable Development Goals (SDG) number 1 (No Poverty), 2 (Zero Hunger), 3 (Good Health and Well Being), 6 (Clean Water and Sanitation), 13 (Climate Action), and 15 (Life on Land). Based on our analysis, we also concluded that agriculture planners in Nepal should increasingly use food system foresight thinking and scenario planning in designing and implementing long-term agriculture and food sector development. This broader nexus approach is based on normative (backcasting) scenario planning and participatory decision making in food system actions. It, thus, also makes food systems inclusive from gender and social points of view.

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