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Role of integrated crop-livestock systems in improving agriculture production and addressing food security – A review

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ABSTRACT

Integrated crop-livestock systems (ICLS) can be productive, sustainable, and climate-resilient agricultural systems compared to specialized and intensive systems. This review explores the beneficial traits and contributions of ICLS to food security, social and economic benefits, and resilience, and proposes strategies to adopt ICLSs in low-, medium-, and high-income countries. Currently, global food security faces two main challenges. First, one in nine people do not have sufficient protein and energy in their diet, of those 50% are smallholder subsistence farmers and 20% are landless families in the low-and medium-income countries (LMICs). Second, specialized intensive agricultural practices often cause soil and environmental degradation. ICLS is an agricultural practice that could play a significant role in mitigating these challenges. The diversified cropping systems in ICLS can improve the productivity of the principal crop as well as enhance food security through increasing nutritional indicators such as food consumption score and household dietary diversity especially for rural households. An ICLS, therefore, could be a key for achieving food and nutritional security and environmental sustainability both in short and long-terms. While ICLS practices have increased over time, there are still adoption challenges due to lack of investment, sustainable awareness, lack of skills by the producers, and market competition. In LMICs, successful implementation of ICLS requires organizational and/or institutional support to create new marketing opportunities and adoption of ICLS can be improved if government policies provide capital, markets, and educational services to subsistence farmers. These government policies can also increase the producer's knowledge, change farmer's attitudes and enhance trust in organic matter management for sustainable soil management. Therefore, agricultural scientists are challenged to provide fundamental and credible information to integrate crop and livestock production systems so that worldwide adoption of ICLS can be used to increase the agricultural production compatible with food and nutrition security.

1. Introduction

Food security is defined as the availability of sufficient quantity of food with appropriate quality supplied through domestic outputs or imports to reach a state of nutritional well-being where all physiological needs are met at all times [1]. Food and nutrition security has four dimensions: (i) food availability, (ii) food access, (iii) food utilization, and (iv) food stability [1]. Food availability alone does not assure access to food with enough calories and nutrients for dietary needs [2]. Furthermore, high-quality foods often command higher market prices, which could result in increasing global food nutritional problems, especially for low-income people who cannot afford these foods [3]. The global human population has doubled from 1960 to 2010 and is projected to reach about 9.7 billion by 2050, and 10.9 billion by the 2100 [4], presenting significant challenges for global food security due to a significant increase in the global demand for food [5]. In addition to insufficient food supply and low income from small farms, unsafe and insufficient nutrient supply from food complicates food security achievement for low income people.

About 50% of the undernourished people are smallholder subsistence farmers and 20% are landless families who are mostly agricultural laborers in low- and medium-income countries (LMICs) [6]. In Asia, China accounts for approximately 50% of the world's smallholders, followed by India with 23%, and Indonesia, Bangladesh, and Vietnam

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[7]. These smallholders account for 380 million farming households, hold roughly 30% of the agricultural land, contribute up to 70% of the food calories produced in LMIC, and are responsible for the 53% of the global food calories production for human consumption [8]. These smallholders often practice indigenous agriculture either with crop production or livestock husbandry with little off-farm inputs and minimal amounts of land. Often the land is of poor quality due to suboptimal management and fragmentation through multiple generations [7].

Globally, the main sources of food have shifted in the past 50 years from grains to animal protein, which has increased livestock production significantly [9,10] even though this decreases energy efficiency. With global populations rising rapidly, global agriculture faces the challenge of producing enough food to meet increasing demand in conditions of changing climate and natural resources depletion [7,11,12]. Misuse of natural resources (excessive and destructive use) results in greater depletion and environmental pollution, which negatively impacts food security in the near and long-term for all consumers [13]. In last 70 years, pressure on agricultural land has increased considerably due to agricultural modernization, industrialization, and mechanization which has increased the environmental problems. This industrialization has led to specialized intensive cropping systems, short crop rotations, intensive grazing, overuse of machinery and inappropriate agricultural management practices can result in water pollution, soil erosion, lack of pollinator habitat, and offsite contamination.

Specialized farming which refers to "only one kind of farm business such as growing food or feed crops or rearing sheep or dairy cattle", with "the primary motive being profit to survive and support their households" [14]. Under specialized crop farming, fertilizers and pesticides are primarily relied on for crop health, if improperly applied, which can result in water, air and natural ecosystems pollution [15] and the contamination of food products [16]. The specialized, simplified, and concentrated crop and livestock farms can contribute to reducing biosphere integrity [17], overgrazing, or intensive grazing which can cause both soil degradation by livestock trampling [18] and environmental problems due to animal waste disposal and use of antibiotics and hormones. The environmental contaminants and pollutants can increase human health risks and negatively impact food security.

Sustainable agriculture as an alternative to intensive specialized agriculture can increase productivity and profits without having adverse impacts on the environment. An integrated crop-livestock system (ICLS) is considered a sustainable agricultural system that can help in enhancing food security. The ICLS manages crops and livestock on a single farm [19]. Seo [20] reported that a farm practicing ICLS is more resilient under global warming than a farm specialized in crops or livestock. He predicted that the specialized farm net revenue falls as much as 75% under changing climate scenario, whereas the mixed farm net revenue falls only by 10% for the same climate scenario. For example, Maughan, Flores [33] conducted an experiment on ICLS and found that integrating crop and livestock increased corn grain yield (11.5 Mg ha^{-1}) compared to continuous corn (10.8 Mg ha^{-1}).

The whole output from the ICLS is greater than the sum of its components because the output of one land unit is used as an input for another part of the system and can raise the overall efficiency of the farm and productivity of both the crop and livestock production components [27]. For example, ICLS can effectively use crop residues as fodder for livestock [3,21], while the livestock can improve soil fertility through their manure and urine deposition if managed properly [22] (Fig. 1). McKenzie, Goosey [34] conducted a 3-year experiment to compare the effects of sheep grazing for cover crop termination and an alternative source of revenue. They reported that the mixture of cover crops (buckwheat, beets, sweet clover, and pea) provided high-quality forage for sheep with a potential value of 144.0–481.80 USD ha^{-1} of direct revenue as a grazing lease. Manure application from livestock in the ICLS increases nutrient cycling and places less reliance on synthetic fertilizers within-farm [30]. Draught animals also improve working conditions of small land holders, provide transportation, and increase agricultural productivity [23]. The ICLS can provide sustainable intensification for both crop and livestock production systems and alleviate food insecurity [20,24–26].

This necessary integration between crop and livestock production

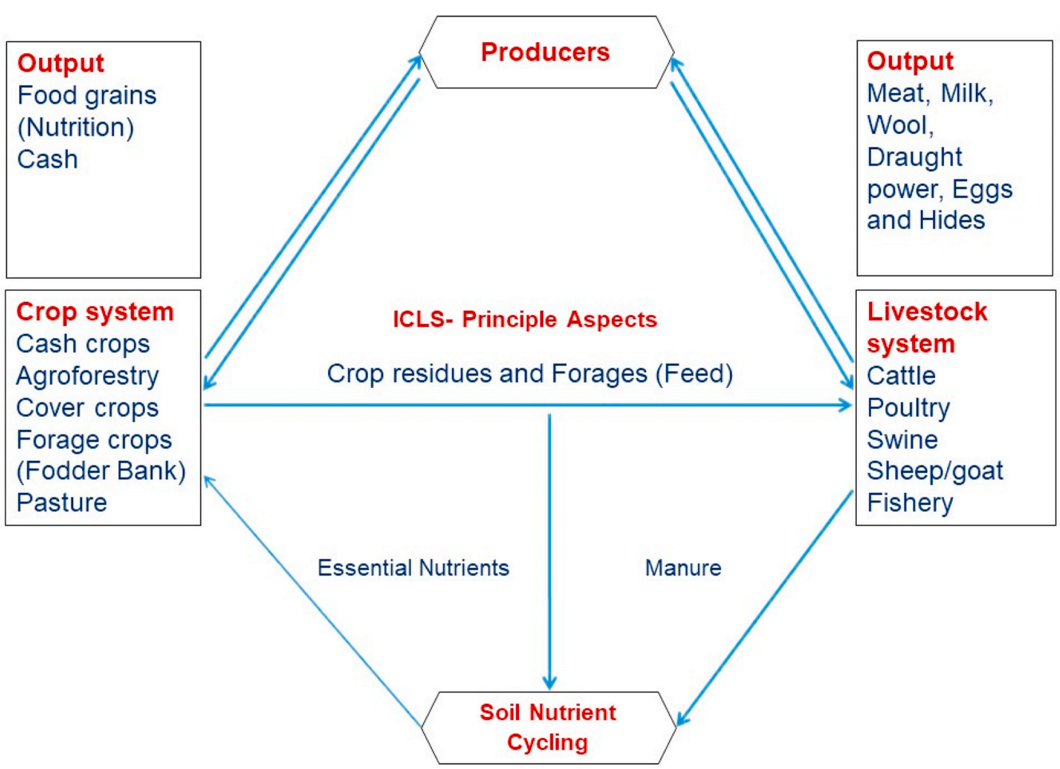

Fig. 1. Principle aspects of the integrated crop-livestock system (ICLS).

can be achieved at the field, farm, and regional levels where the sustainable food and nutritional security starts [28]. At the field scale, the ICLS strives for a closed nutrient cycle where manure from grazing animals are used for nutrients and supply organic matter for improving soil fertility, whereas cropland produces various fodders that are consumed by livestock [29]. At the farm scale, crops and livestock are spatially separated [29]. At the regional scale, distant farms share nutrients by moving crops and manure among farms [30]. Typically, various types of ICLS involve diverse cereals or cover crops, beef cattle and dairy cows, buffalo, poultry, sheep, and goats (Table 1) due to different purchasing powers and knowledge of ICLS management of producers, availability of resources, soils, and climate [31,32].

Diversifying production could also utilize labor more efficiently at the farm and/or regional scales. According to Katsvairo, Wright [35], compared to monoculture crop production systems, ICLSs have greater soil quality, crop yield, and economic returns (5179 and 30802 USD, respectively) in the southern United States. Tracy and Zhang [36] reported that ICLS significantly increased corn yield (11.6 Mg ha^{-1}) compared to continuous corn (10.6 Mg ha^{-1}). Soussana and Lemaire [27] concluded that practicing ICLS would avoid negative consequences of agricultural production such as the loss of biodiversity and large carbon footprint of industrial technologies. ICLS can produce a diversity of foods, augment pollinator populations, and aid pest management [37], thereby increasing food products when the land size is held a constant. ICLS can reduce soil erosion, increase soil biological activity, and maintain soil fertility [38]. For example, Allen, Baker [39] found that ICLS reduced 40% of nitrogen fertilizer input, increased net returns above 90%, and reduced soil erosion (<7 Mg ha^{-1} yr^{-1}) compared with monoculture system (19 Mg ha^{-1} yr^{-1}).

Reintegrating crop and livestock have been a subject of renewed

Table 1
Different types of crops and livestock used under the integrated crop-livestock system (ICLS) in different parts of the world.

Ecological/Climatic zone/Place/ Research Carried out	Crops	Livestock	Major livestock output	Location	References
Humid	Cassava, Maize, Banana, Rice Groundnut, and Oil Palms	Cattle, sheep, goat	Meat, milk, and power	Sub-Saharan Africa, West Africa	Saleem [79]
Sub-humid	Maize, Millet, Groundnut, Cassava, Beans, Rice, and Sorghum				
Arid/Semi-arid/Sub humid	Millet, Banana, Beans, and Maize				
Arid	Sorghum, Millet, and Beans				
Cool tropics	Teff, Wheat, And Oats, Maize, and Pulses				
Cauvery Delta zone, Northwestern zone of Tamil Nadu and Northwestern arid region of Haryana	Paddy, Sugarcane, Vegetables, and Flowers	Cow, Buffalo, Goat, Piggery, Sheep, Poultry, and Fishery	Milk, Calf, Chicken, Fish, and Meat.	India	Ponnusamy and Devi [26]
North West India	Rice and Wheat	Buffalo, Cattle, and Goats	Milk and Meat	India	Kumar, Ansari [38]
University of Illinois, Pana, Illinois,	Corn, oat, Cereal rye and Turnip	Beef cattle	-	USA	Maughan, Flores [33]
Montana State University-Bozeman	Kohlrabi, Spinach, lettuce and Cover crops (Buckwheat, Beets, Sweet clover and Pea)	Sheep (Grazing)	-	Bozeman, USA	McKenzie, Goosey [34]
Southeastern USA	Corn, Soybean, and Wheat (Winter cover crop)	Cattle		Georgia, USA	Sulc and Franzluebbers [112]
The Texas Southern High Plains	Old world bluestem (grass), Cotton, Rye, and Wheat	Steer	-	USA	Allen, Baker [39]
Southern Coastal Plain	Cotton, Peanut, and Rye or Wheat or Crimson clover (Cover crops)	Steer and Heifers	-	Georgia, USA	Franzluebbers [24]
Southern Piedmont	Sorghum, Wheat, and Rye and Pearl Millet or Crimson clover (Cover crops)	Cattle and Broilers	Meat	USA	
U.S. Corn belt, Pana, Illinois.	Corn, Oats, Cereal Rye and Turnip	Beef Cattle		USA	Sulc and Tracy [40]
Mississippi	Trees, Corn and Perennial forages (Agroforestry)	Dairy cow	Milk	USA	Sulc and Franzluebbers [112]
North Dakota	Oat/alfalfa/hairy vetch/red clover, Brown midrib sorghum–sudangrass/ sweet clover/red clover and Corn	Cattle	-	USA	Liebig, Tanaka [117]
Southern United States	Peanut, cotton, and bahiagrass/ bermudagrass	Cattle			Katsvairo, Wright [35]
South-eastern and North-eastern Tablelands and slopes, and The Southern and Western high rainfall zones	Wheat and Canola (Dual purpose crops)	Beef cattle and Sheep	-	Australia	Bell, Harrison [118], Bell, Moore [119], and Dove, Kirkegaard [120]
Brazilian subtropical region (Southern Brazil), Tropical region	Soybean, Corn, Rice, Beans, Eucalyptus (Agroforestry), Cotton, Wheat (Winter cover crop) and Signal Grass (Pastures)	Beef Cattle, Dairy Cattle, Sheep	Meat, Milk, Wool	Brazil	Rodriguez, Cox [121], Villano, Fleming [122] de Faccio Carvalho, Anghinoni [123], Gil, Siebold [124], Salton, Mercante [125]
Southeast, Midwest, Northeast and (North of Brazil), Mato Grosso do Sul					
Coteaux de Gascogne (Hilly region)	Cereals and other cash crops	Beef and Dairy Cattle	Meat and Dairy products	France	Ryschawy, Choisis [126]
Charolais suckler cattle farms in central France	Cereals, Sunflower, and Rapeseed	Beef Cattle	Meat	France	Veysset, Lherm [127]
Canterbury	Wheat, Brassicas, Kale, Fodder beet, Oats, Barley, Peas, Beans, Turnips, and rapeseed	Beef cattle, Dairy cattle, Sheep, and Deer	Milk, Tallow, Potted and Salted meat, Wool, Skins, Hides, and Lamb	New Zealand	Dynes, Burggraaf [128]
Marlborough	Wine grapes (Viticulture)	Sheep	-	New Zealand	Niles, Garrett [44]

interest in recent years with the purpose of inventing modern ICLS that are capable of providing both high socio-economic outputs and multiple environmental benefits based on current technologies [29,30,40]. Many aspects of ICLS, including regional and country specific studies have been reviewed [19,30,32]. Web of Science literature search using keyword 'integrated crop-livestock systems' returned a total of 1097 hits. Some of the key reviews and studies are used in this review to provide the background of this study. However, this review takes a slightly different approach by emphasizing the potential role of ICLS in addressing some of the food security concerns, especially in the developing world. While advantages, challenges, and opportunities of ICLS at the farm and beyond farm level have been widely studied [22,26,32,41,42], the role of ICLS in addressing global food security has not been fully assessed. Indeed, searching among 1097 hits using key words 'food security' and 'resilience' returned 92 and 15 hits, respectively. Among the ICLS hits, we did not find any article which exclusively addressed the role of ICLS on enhancing food security. Therefore, the objective of this review is to highlight the potential role of ICLS in addressing food security. Specifically, the following questions are addressed:

- What are the major components of ICLS and how do they beneficially interact to address food security problems and environmental challenges?
- Could ICLS be an option to achieve food security for better human health?
- What are the social and economic benefits of ICLS?
- What are the challenges to adopt ICLSs and what strategies could be used in LMICs and high-income countries to overcome adoption barriers?

2. ICLS advantages, disadvantages, and development

2.1. ICLS advantages and disadvantages

The agricultural sector has been undergoing major changes as a response to increasing demand for food, higher production costs and a more competitive market, requiring an increase in yields, quality and profitability, without harming the environment. In order to achieve these goals, one of the alternatives that has gained interest in recent years is a return to integrated systems that incorporate crop and livestock farming in a temporal and/or spatial framework [24,29,30]. These systems strive for synergies among the agro-ecosystem components for farm sustainability, while providing ecosystem and environmental services, and valuation of natural capital [26,43]. In addition to general benefits of agricultural intensification and production system diversification, ICLS also offers food and nutrition security-related advantages. These may include: (i) increased economic return. A study from India revealed that the adoption of multiple farm enterprises like crop, dairy, poultry, and fish increased farm net profit by 660 USD per year compared to a less diversified crop only [26]. (ii) Income stability, i.e. reduced economic risks through multiple production systems. (iii) Reduced inorganic fertilizer, pesticide and other inputs. According to Niles, Garrett [44], integration of sheep in vineyards reduced mowing and herbicide use and saved 64 USD per hectare. Another economic benefit of ICLS is the reduction of fertilizer costs and increased forage supply because manure can be used as a source of recycled nutrients, and crop by-products such as straw and cover crops can be used for feeding livestock [22]. (iv) Improved human nutrition. ICLS can help supply all the food needed, both grain and animal protein, for family members of smallholder farmers in LMICs countries. Animal-source food (ASF) provides both high quality protein and bioavailable micronutrients. (v) Increased soil health through increased SOC storage thereby improving agriculture sustainability and minimizing agriculture environmental impact [44].

Environmentally, ICLS can increase carbon (C) accumulation and biodiversity [27,30] and have the potential to reduce GHG emissions thereby strengthening environmental sustainability [19]. Acosta-Martínez, Zobeck [45] investigated the influence of continuous cotton and an ICLS on soil properties in Texas, USA, they reported that ICLS increased soil microbial biomass (237 mg kg^{-1} soil) compared to continuous cotton (124 mg kg^{-1} soil). They also found that SOC (13.5 g kg^{-1} soil) was significantly greater with ICLS compared to continuous cotton (9.0 g kg^{-1} soil). ICLS often improve farmer's income and employment opportunities in rural areas [32]. However, benefits depend on crops, livestock, soils, local conditions, and management methods. The ICLS could be a new opportunity to re-introduce livestock to farms, create a complementary system where livestock and crops provide dual income to producers and help in changing crop rotations to reduce the risk of total crop loss due to changes in weather patterns associated with climate change (Table 2).

Despite several advantages to ICLSs, there may also be disadvantages in some situations, one of which is that ICLSs can be complex to operate and manage. ICLS demands a greater knowledge (both crop and livestock) and commitment as livestock need continuous (constant) care from people involved in the operation [46]. Other potential negative impacts of ICLS include soil compaction, which reduces the crop growth and affects the growth of succeeding new crops. Cattle grazing can cause soil compaction if they are allowed to graze when the soil is too wet, therefore, management strategies encourage residue grazing only when the soil is dry [47]. Niu, Zhu [48] found that soil compaction was significantly greater with overgrazing (1983 $\pm$ 192 kPa) than that of a properly managed grazing site (1044 $\pm$ 188 kPa). The inherent nature of ICLSs often implies competing uses of crop residues since they are not only used as feed but also as mulch, fuel, and construction material [49]. Such trade-offs are often dependent on the socio-economic status and context, including factors related to the availability and demand of crop residues and farmers' preferences [50–52]. Intensive grazing of pasture can lead to the dominance of poorly productive, short cycle species in rangelands. This can reduce livestock production and affect the nutrient transfers to croplands, which in turn can reduce crop residue availability for livestock [53]. Increasing demand for the fodder, low availability of arable land and water, combined with less availability of resources put more pressure on the feed resources [54]. Potentially, ICLS can lead to poor distribution of nutrients from manure and urine, leading to uneven crop growth. Continuous labor and infrastructure requirements, high capital investment, and increased nutrient losses through intensive recycling are also the major disadvantages of ICLSs.

2.2. ICLS development

The development of ICLS varies globally. These systems were once common in most parts of the world and were developed 8 to 10 millennia ago [55]. In the Middle East and Southern Asia, draught animals were used to plow, transport, draw a sledge, and increase crop production during 6000-4000 BCE [57]. In China, the earliest records of the integrated crop, tree, livestock, and fish farming was from the Shang-West Zhou Dynasties of 1600–800 BCE [56]. In Europe, ICLS practices formed the historical basis for the agricultural revolution in the middle ages (two-year crop rotation with livestock grazing during fallow period) in the 16th century [29]. Over the last century, however, technological advances and economies-of-scale led to rapid farm specialization globally, resulting in a reduction in the share of ICLSs, especially in high-income countries. However, ICLSs have been increasing recently as researchers try to find a balance between sustainability and resilience of agriculture production in the global warming era [58–60]. For example, in the USA during the 1990s ICLS was practiced on less than 10% of the agricultural land [61]. In 2010, the United States Department of Agriculture (USDA) reported that grazing corn (*Zea mays* L.) residue represented 12% of the total corn acreage across 19 states but most often occurred in the western Corn Belt Region [62]. Based on another survey in 2015, about 70% of ranches grazed crop residue (one of ICLS methods) in the Northern Great Plains, USA [63]. In LMICs, ICLS is an

Table 2
Reports on the benefits of integrated crop-livestock systems (ICLSs) in Western Europe and South America [adapted from Ref. [32]], Southern Australia [adapted from Ref. [41])], and North America [adapted from Ref. [30]].

Western Europe and South America	Southern Australia	North America
• A new opportunity: reintroducing livestock to farms or territories specialized in cereal production	• A complementary system: Livestock and cropping can provide dual income to a farm to mitigate risk in poor seasonal or bad market conditions	• Changing crop rotations: fixed annual crop rotations can suffer from weaknesses that are expressed under stressful weather conditions and pest infestations
• Using pastures for recycling nutrients and regulating environmental flows	• Nitrogen fixation and transfer: Crop-pasture systems have relied on legumes to fix and supply nitrogen	• Reducing the risk of environmental damage during the perennial cropping phase by decreasing nitrate losses
• Using forage and legumes for increasing N and energy efficiency	• ICLSs with perennials can provide year-round use of rainfall, solar radiation, water, and nutrients, whilst maintaining ground cover	• Reducing yield losses from insects and diseases
• Using catch crops and permanent cropping to manage N better	• Reducing damage to soil aggregation and compaction compared with continuously grazing the pasture, increasing microbial biomass, accumulation of organic matter, promoting microbial diversity, and forming a more suitable environment for the coexistence of soil microorganisms.	• Improving the resilience of cropping systems with forage legumes
• Efficient recycling of animal waste to reduce mineral N utilization	• Controlling weeds, pests, and diseases	• Most critical in organic crop production
• Transferring nutrients between neighboring farms to manage their liquid manure	• Providing greater continuity of plant production and opportunity to fill feed gaps; deep-rooted perennial pasture in ICLS can effectively control drainage and dryland salinity problems	• Integrating livestock can increase economic return and the rate of soil C accumulation and reduce stream sediment loads
• Complementarity between specialized livestock farming systems (mainly pigs) and cereal farms may be considered on a broader geographical scale	• Trade-offs between profit and environmental outcomes abound in agricultural and other production systems; a win-win situation can be achieved; many studies have reported economic benefits from ICL systems	• Within-farm integration and regional (among-farm) integration: choose the best integration based on real nature and scale of integration
• Drying slurries (solid manure) can produce normalized fertilizers	• Improving sub soil macro-porosity and increase yields in subsequent crops	• Improving manure use: both N and P can cause environmental problems when applied excessively

important agricultural practice and also has been increasing in some countries [64]. For instance, most of the dryland farming systems of Sub Saharan Africa use ICLSs [65]. In Southeast Asia, nearly 75–90% of the ruminant livestock are raised on ICLSs [66]. In Brazil, over the last 10 years, the area of ICLSs has doubled [67]. Therefore, understanding the synergistic effect of ICLS contribution towards food security is important and a greater research effort is required to investigate the impacts of ICLS on food security.

3. Contributions of ICLS towards food security

3.1. Role of crop-livestock interaction in sustainable food production and food security

In marginal environments, crop-livestock interactions can contribute to a stable increase in both food crop and livestock production [66]. Currently, milk and meat produced from animals provide 13% calories and 28% protein consumed worldwide. In addition to the dietary needs such as meat and milk, ICLS produces 50% of cereals. In most ICLS, the major animal feed consists of crop residues. Production of more crop residues under ICLS can be utilized as feed for livestock without competing with people for food [68]. For example, under ICLSs in Africa and Asia, smallholder farmers use their cereal grain residue for livestock feed and allow part of the residues to remain as mulch [52]. In poor rural households, livestock are often considered an important asset. Accumulation of livestock allows poor households to invest in small businesses, diversify their income, and become less poor, all of which tend to enhance food and nutritional security [69].

3.2. Diversity of crops in ICLS to achieve food security for better human health

The diversified cropping systems in ICLS can improve the productivity of the principal crop and enhance food security and nutrition indicators such as food consumption score and household dietary diversity [70]. Diversity in ICLS with the rotations of cover crops and nitrogen-fixing crops can increase protein content of vegetation and enhance the diets of livestock, thereby benefiting human health [70,71]. A study from the subtropical region of Brazil found successful ICLS with crop rotation of soybean and maize or rice as summer crops with winter annual grazing [58]. Integrating grasses and legumes with crops can enhance system productivity and resilience and improve livelihoods [72]. Gill, Singh [73] reported that integrating crops + dairy and crops + dairy + poultry production system doubled production (25.0 and 25.5 t ha^{-1} crop equivalent yield, respectively) compared to monoculture cropping (12.5 t ha^{-1}). However, increased production does not necessarily lead to improved human health, especially in resource-limited situations, where assets and income must meet many needs.

From the perspective of smallholders in the LMICs, ICLS with the diversification of crops has a direct effect on food availability and nutrition through enhancing crop yields while also providing crop yield stability and farming insurance effects [25]. A study from Malawi showed that smallholder households using intercropped legumes resulted in improved child growth (weight-for-age Z-score from −0.4 to 0.3) compared to control households that did not use this cropping strategy [74]. Inter-species diversity ICLS (i.e. different species) within the farms, for example, will likely be more nutritionally meaningful than intra-species diversity (i.e. having similar crops) [70]. Diversification strategy which integrates both crop and livestock production adds multiple value directly through increasing quality and diversified diet, and indirectly through income generation to a producer [70]. According to the survey conducted by Romeo, Meerman [70], it was reported that among the households practicing ICLS, all the households consumed cereals and vegetables, 91% consumed fish, 78% consumed pulses, 62% consumed fruit, 65% consumed milk, 41% consumed meat, and 32% consumed eggs. In addition to achieving dietary requirements, pulses, vegetables and fruits, and livestock serve as a risk management tool, protecting farms against climate change and market variability and increasing the farm resilience. Jones, Shrinivas [75] reported that including livestock within the cropping system resulted in a positive relationship between farm and household dietary diversity. Similarly, Wright, Tarawali [76] reported that market access, off-farm income, and selling and buying food from the market also have positive effects on dietary diversity, which are larger than those of increased farm production diversity. Market transactions tend to reduce the role of farm diversity for household nutrition. Sibhatu, Krishna [77] reported that households in remote regions had lower dietary diversity than those close to the market where food can be sold or bought. They also reported that producing one additional crop or livestock species leads to 0.9% increase in the dietary diversity. Cash earnings from off-farm activities by the many smallholders increase the households' ability to buy diverse foods from the market [77].

3.3. Role of livestock on food and nutrition security under ICLS

Livestock play a key role in the functioning ICLS farms through directly providing ASFs such as meat and milk [78–80]. These ASFs are one of the most important food sources that can satisfy the protein needs of human [81,82]. ASFs are nutritionally rich source of energy, protein, and various essential micronutrients, whereas plant-based diets tend to be deficient in one or more essential amino acids, especially lysine, methionine, and threonine [83]. Also, more bioavailable micronutrients including iron, vitamin A, vitamin B12, and calcium are naturally found in ASFs, and they are associated with stronger immune systems and healthier immune responses [83]. Consumption of even small quantities of ASF has been shown to contribute considerably to ensuring dietary adequacy and averting under-nutrition and nutritional deficiencies [84]. ASF can positively impact growth, cognitive function, and physical activity of children, have better pregnancy outcomes, and reduce morbidity from illness [84].

Romeo, Meerman [70] suggested that supporting investments in ICLS with livestock such as goats and sheep are viable interventions for enhancing food and nutrition security of households. The ICLS account for most of the food grains, meat and milk production in Asia, and 40–60% of the cattle, sheep, goat, and poultry meat production in sub-Saharan Africa [85]. Udo, Aklilu [86] conducted a case study on impact of intensification of different livestock production in smallholder ICLS. The results from these case-studies indicated that integration of dairy cattle within smallholder ICLS provided largest benefits (400 to 1030 USD y^{-1}) compared to the poultry (70 USD y^{-1}) and small ruminant systems (120 to 165 USD yr^{-1}). High demand for the milk in the market is the major factor favoring integrating dairy cattle in the smallholder ICLS.

3.4. Social and economic benefits of ICLS and their role on food security

The ICLS is intended to enhance sustainable development and ensure that these systems are environmentally sound, economically beneficial, and socially appropriate [87]. As discussed in section 2, ICLS can result in substantially higher profitability, compared to specialized crop or livestock production. The benefits of ICLSs, however, depend on the stability of markets, technologies, social culture, infrastructure, labor availability, policies, and biophysical and climate factors [31]. For example, in North Dakota, USA, labor and management earnings were 12,304 USD for crops only (monoculture) and 18,063 USD (46.8% higher) for ICLS where crops and cattle operations were integrated, even with a modest return from the cattle in 2001 [88]. The data collected during 2000s showed that diversified ICLS improved total revenue of the farm (330 USD ha^{-1}) compared to the specialized farming practice (170 USD ha^{-1}) [89]. A study from Texas, USA, showed that savings from reduced irrigation (<23%) and reduced fertilizer application (<40%) in an integrated cattle-cotton system recorded 90% higher profitability (362.17 USD ha^{-1}) than the cotton-only monoculture (190.91 USD ha^{-1}) [90]. A survey conducted by Seo [20] indicated that ICLS will become relatively more profitable (695.54 USD ha^{-1}) than specialized farming system (291.21 to 458.57 USD ha^{-1}) half a century from now.

Small-ruminant production has been perceived as an income-diversification strategy where sheep and goats are kept as capital stock and can also provide income in case of crop failure [91]. In Sudan, for example, there is a growing domestic and export market for live sheep and meat, and this has resulted in integrating crop production system into sheep raising, which in turn finances the crop production [92]. Moreover, small-ruminant production has social and cultural significance. For instance, in Ghana, chevon, mutton, and chickens not only are major sources of household meat but also have a socio-cultural implication. These animals can be used for traditional festive occasions such as marriages, naming ceremonies, and other festivals, which enhances the value of these animals across the country [91].

In LMICs, ICLSs mainly contribute to food security by increasing the income of poor subsistence farming communities [93]. Approximately 70% of people living in poverty are from subsistence rural farming communities [6]. The ICLS can increase the income of these communities through employment along ASF value chains [93]. In Africa, the smallholder incomes derived from livestock under ICLS constitute 34–87% of total farm income [94]. These incomes support the purchase of other high-quality foods, farm inputs (e.g., fertilizer, pesticides, and seeds), animals for restocking, and other household's requirements for future ICLS production. The diversified food production from the single farm nearly guarantees the family's food security while also contributing in meeting the basic family needs [7,97]. Tipraqsa, Craswell [98] calculated the food expenditures under ICLS and specialized farming and observed that food expenditure was greater under the ICLS (257 USD y^{-1}) than the specialized farming (196 USD $year^{-1}$). However, when expressed in per capita terms then the food expenditures are 66 USD per capita for ICLS and 73 USD per capita for specialized farming (which is about equal for both farming systems). The results also showed that the share of food produced at home is significantly greater for the ICLS than for the specialized farming (ICLS = 68% and specialized farming = 33%). These results suggests that the ICLS which has a greater number of food species is more secure in the food supply than the specialized farming [98]. The synergetic interaction between crop and livestock offer various opportunities for increasing the utilization and efficiency of the resources and increasing productivity, thereby increasing household incomes and securing availability and accessibility to the food [25]. Household members under ICLS tend to be better nourished because of a more diverse diet [98]. The incomes controlled by women from ICLS are more likely to be spent on their children or family's nutrition [12]. In Africa, for example, where women tend to own the majority of livestock, the sale of small stock such as sheep, goats, and poultry by women during financial crises and/or grain shortages contribute to overall food security of the family [95]. According to FAO [96], improving women's access to inputs and services has the potential to reduce the number of malnourished people in the world by 12 to 17% or 100 to 150 million. Therefore, ICLSs not only provide a diversity of foods for human diets but also enhance producer income, especially poor farmers' incomes, thus improving the purchasing power of the household for buying other quality foods [99–101]. This makes ICLS a vital option in improving food security.

4. ICLS and climate resilience

Bullock, Dhanjal-Adams [102] defined resilience in terms of food security as maintaining production of sufficient and nutritious food in the face of chronic and acute environmental perturbations. Over the coming decades, the areas especially under dry climatic conditions will experience a rise in temperatures, frequent droughts, and increasing water scarcity [103]. Arid and semiarid regions are more vulnerable to extreme weather conditions and human activities [39]. This could lead to declines in agricultural productivity, shorter-growing seasons, and less arable lands for cultivation [104]. For example, some models predicted that if air temperature increases by 4 °C, the growing seasons of dry regions may be shortened by 20%. Further consequences of climate change include higher poverty, food and nutrition insecurity, instability of food production, and a greater dependence on food imports from foreign countries [104]. However, the sustainable ICLSs especially in LMICs, with a strong market orientation could be a key driver to increase both crop and animal productivity under changing climatic scenarios. The key to success is of this type of system is to sustainably use natural resources which would improve livelihoods and food and nutrition security [104–106].

The sustainability of livestock production also may be affected by the climate change, therefore, a clear understanding of the long-term challenges of climate change are essential for successful management [107,108]. The major problems for livestock are likely to include decreased rangeland productivity, increased disease incidents, demand for land, and strain on water resources. ICLS can protect each sector from external pressure from changing climate scenarios and optimizing social, economic, and environmental conditions in resource-poor regions. ICLS encourage farm resilience to climate change via buffering mechanisms in both field and farm-level processes, e.g., improved crop productivity, nutrient cycling, economic risk mitigation, and livelihood diversification. A survey conducted in Africa to predict the influence of climate on 2060 African farming systems forecast that farms under ICLS will increase sharply in the future [20]. Crop mixtures integrated with multiple livestock species can achieve greater yield resilience than specialized crop or animal production [72,102]. ICLS allows flexibility in crop, forage, and livestock husbandry selection and can be further improved by implementing new technologies in response to changing conditions. At the global scale, farm resiliency can be achieved through ICLS knowledge transfer to and among farmers, enhancing social networks, and allowing self-organization of the farmers to address agriculture resilience in an adaptive fashion [102,109].

5. ICLS adoption strategies

The contributions of ICLSs to global food security could provide huge opportunities to adopt a wide variety of ICLS practices [109–112], but there are challenges that must be addressed. Therefore, it is vital to select proper ICLS adoption strategies to meet these challenges.

5.1. ICLS adoption strategies of smallholders in LMICs countries

The smallholder subsistence farmers in LMICs are willing and attempting to integrate crop and livestock production to maximize returns from their limited cropland area and resources [111]. However, ICLS adoption under smallholder farms faces challenges, including: (i) reduction in grain yield under ICLS-often observed under crop-pasture intercropping, as annual crops compete with the pasture for below-ground and above-ground resources during the growing period. This competition has led to the development of pasture cropping system which aims to achieve a complementary combination between main crops with active growth during winter and summer active pastures [113], (ii) management decisions and strategies to utilize the full benefits of ICLS. The management system must ensure that trade-offs are properly balanced in these systems to achieve the overall goals of the enterprises [110]. This can be achieved through better understanding of the individual elements and their interactions with one another in given time and space, which is sometimes not easy to achieve due to the knowledge gaps, (iii) specialized crop producers are not willing to take on the additional decision-making complexity involved under diversified ICLS, (iv) With the increasing demands for ASFs [3], smallholders in LMICs are often unable to respond to the growing markets. This is primarily because population increase results into intensification of land use, loss of grazing areas and shrinking farm sizes [86]. These hamper their ability to have extra livestock products for sale, (v) the increasing demands for livestock products in most markets are satisfied by today's industrialized production systems [86] which would limit sales from smallholder farm operations. Although governments have remained committed to poverty alleviation, smallholder farmers in developing countries are still facing food insecurity problem [114], and (vi) small scale resource-constrained farmers face challenges in the availability and accessibility of genetically modified crops and animals and their integration with ICLS [115].

To meet ICLS challenges, government support and specific policies protecting subsistence smallholder farmers are key to smallholder farmer's success in this venture. The government support and policies should provide farmers with (i) capital support such as micro-credit, livestock in-kind loans and government subsidies, (ii) increase research investment in livestock production technologies and management, (iii) create markets and support services to facilitate the sale of their farm products, (iv) raise the awareness of people the resilience of ICLS and (v) offer farm insurance. Successful adoption of ICLS requires development of management strategies that promote crop-livestock synergism and improve their interactions aiming at: (i) integration of crop and livestock effectively in the same farm within the given land, (ii) increasing the productivity of ICLSs, (iii) facilitating expansion of food production and infrastructure facilities (meat plants and cold storage) while also mitigating the environmental impacts and encouraging efficient use of natural resources, (iv) developing a sustainable livestock manure management system to control environmental pollution, and (v) reducing the pressure on natural resources and implementing a more efficient use of resources within the ICLSs. Without some logistical and policy supports that deliberately consider the opportunities and challenges, many of the smallholder farmers are likely to be excluded from ICLS and the increased market opportunities [86].

5.2. ICLS adoption strategies in high-income countries

Some of the major challenges for the adoption of the ICLS in high-income countries include: (i) higher initial costs under ICLS than a single specialized operation. This created disincentives to adopt ICLSs, (ii) ICLS adoption requires a supply chain infrastructure, greater managerial intensity, knowledge, skills and capital than either continuous cropping or livestock [19,30,41,112]. Often the higher initial investment cost and lack of infrastructure make producers unwilling to adopt dedicated diversified cropping systems, including ICLS [61], (iii) social and environmental attitudes, limited awareness and lack of knowledge of ICLS practices [116], (iv) traditional production methods cropland management policies that restrict the conversion of agricultural systems into ICLS practices. Generally, the adoption of ICLS is limited to producers who have both animal and crop production skills [61,116]. Similarly, most consumers are looking for cheaper products and are not willing to pay the higher price for sustainably produced products. Therefore, adoption and expansion of ICLS practices in high-income countries requires larger capital investments through loans or government subsidies. To achieve higher adoption rates, producers must recognize the comprehensive benefits and contributions of ICLSs to food security, as well as master the skills of crop and animal production in ICLSs. Therefore, outreach programs that provide training and education as well as demonstration about ICLS while improving farmer's knowledge and skills are needed. Research and demonstrations that reinforce benefits and sustainability of agriculture under ICLS as well as addressing adoption challenges would also enhance adoption of ICLS.

6. Conclusions

The adoption of an integrated crop and livestock system for a farming enterprise can ensure a substantial income generation and diversified food to sustain the livelihood of farmers if properly managed, especially LMICS. ICLS can influence the diversity of household diets and support incomes of smallholder subsistence farmers and reduce economic risks. Reintegrating crop and livestock systems can provide many potential benefits such as high socio-economic outputs and an improved environment. However, adopting ICLS demands a significant commitment and knowledge about crops and livestock. Participation of women in ICLS in LMICS improved income generation and increased purchase power of quality foods for their children or family's nutrition.

In conclusion, it is important to understand that expansion of agricultural lands is not an option, especially with smallholder subsistence farmers. On-farm integration of crops and livestock is beneficial to human health by providing nutritious food, and it has social and cultural significance by contributing to food security. To increase the adoption of ICLS, government polices need to support capital investments, infrastructure, and on-field demonstrations, especially for small and marginal farmers, and provide more attention to include small ruminants, protein-rich crops, fruits, and vegetables in the system.

Declaration of competing interest

The authors declare they have no conflict of interests.

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