



SYSTEMIC PERSPECTIVES ON SUSTAINABLE FOOD SYSTEMS:

PRODUCTION EFFICIENCY,
DATA-DRIVEN OPTIMIZATION,
AND DISTRIBUTION FRAMEWORKS

EDITOR

Dr. Otniel Vázquez Peralta



**SYSTEMIC PERSPECTIVES ON SUSTAINABLE
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DATA-DRIVEN OPTIMIZATION, AND
DISTRIBUTION FRAMEWORKS- 2026**

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Dr. Otniel Vázquez Peralta

AUTHORS

Fahad AMJAD

Muhammad ZAIN

Warda AMJAD

Ozioma Faith ORAZULIKE

Flora Onyinyechi UJU-NJOKU

Nnadi Onyinyechi IFEANYI

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Mercy Ihuoma ONYEIKE

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PREFACE

Food systems are increasingly recognized as complex, interconnected structures that extend beyond primary agricultural production to encompass processes of optimization, distribution, and access. In the context of global challenges such as population growth, resource constraints, and food insecurity, the need for systemic and interdisciplinary approaches has become more critical than ever. Understanding food systems as integrated networks allows for more effective strategies that connect biological productivity, technological innovation, and socio-economic organization.

This volume, *SYSTEMIC PERSPECTIVES ON SUSTAINABLE FOOD SYSTEMS: PRODUCTION EFFICIENCY, DATA-DRIVEN OPTIMIZATION, AND DISTRIBUTION FRAMEWORKS*, brings together a set of scholarly contributions that reflect these multidimensional dynamics. The chapters address key aspects of food systems from different yet complementary perspectives. The examination of genetic variation in poultry production highlights the role of biological improvement in enhancing productivity and efficiency. The application of data-driven methods, particularly machine learning techniques, demonstrates how integrated crop–livestock systems can be optimized for more sustainable and resource-efficient outcomes. Furthermore, the analysis of food distribution systems, through the lens of food banks and policy frameworks, underscores the importance of institutional structures in ensuring equitable access to food.

By adopting a systemic perspective, this volume integrates insights from agricultural science, data analytics, and policy studies. It emphasizes the interconnected nature of production, optimization, and distribution processes, and highlights the importance of bridging these domains to build resilient and sustainable food systems.

It is hoped that this book will serve as a valuable resource for researchers, practitioners, and policymakers engaged in food systems, agricultural innovation, and sustainability, while encouraging further interdisciplinary research on integrated approaches to global food challenges.

Editorial Team
May, 2026
Türkiye

CHAPTER 1
**GENETIC VARIATION IN GROWTH HORMONE
MRNA OF IMPROVED NIGERIAN INDIGENOUS
CHICKENS: IMPLICATIONS FOR POULTRY
BREEDING AND PRODUCTIVITY**

¹Jessie Ezekiel UDOH

¹University of Uyo, Akwa Ibom State, Nigeria, jessieudoh@uniuyo.edu.ng

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EFFICIENCY, DATA-DRIVEN OPTIMIZATION, AND DISTRIBUTION
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INTRODUCTION

Poultry genetics has emerged as a cornerstone of agricultural development, particularly in addressing the dual challenges of food security and climate resilience in sub-Saharan Africa. However, traditional indigenous chicken breeds, which constitute 80% of Nigeria's poultry population, often exhibit suboptimal growth rates, high mortality rate due to disease, and poor heat tolerance, undermining productivity in tropical environments (Yakubu *et al.*, 2020). In order to address this gap, genetic advancements such as marker assisted selection and genomic predictions have revolutionized poultry breeding, enabling the development of hybrids with enhanced feed efficiency, disease resistance, and climate adaptability (Gebreyohannes *et al.*, 2021). Central to these traits is the growth hormone (GH) gene, a key regulator of somatic growth, metabolism, and muscle development. GH, secreted by the anterior pituitary gland, stimulates insulin-like growth factor 1 (IGF-1) production, driving cellular proliferation and nutrient utilization in chickens (Scanes, 2021). The FUNAAB Alpha chicken breed raised in the tropical region of Nigeria adapts to the harsh environmental condition of this region. This breed was developed through two decades of rigorous selection at Nigeria's Federal University of Agriculture, Abeokuta (FUNAAB), this exemplifies the integration of genetic innovation with ecological sustainability (Adeleke *et al.*, 2021). It is a dual-purpose breed which was engineered to combine the robustness of local Nigerian chickens such as resistance to Newcastle disease and heat stress with the rapid growth and egg laying capacity of exotic lines (Olanrewaju *et al.*, 2022). Despite its commercial adoption across Nigeria, the molecular basis of its superior phenotype remains underexplored. For instance, while transcriptomic studies in temperate breeds have correlated GH mRNA expression levels with growth velocity (Dehghanzadeh *et al.*, 2023), analogous data for African poultry are limited. This gap disrupts the optimization of breeding protocols for FUNAAB Alpha chickens, particularly in resource-limited settings where genomic tools are underutilized (Lawal *et al.*, 2022). Furthermore, genetic diversity studies in Nigeria's poultry populations reveal significant heterozygosity in growth-related genes, suggesting untapped potential for trait enhancement through targeted selection (Osei-Amponsah *et al.*, 2021).

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Now, advancements in molecular technologies, such as RNA sequencing and CRISPR-based gene editing, create unprecedented opportunities to decode the genetic architecture of productivity traits in tropical poultry (Dzomba *et al.*, 2020). In Kenya, whole-genome sequencing of indigenous chickens has identified SNPs in the GH gene associated with body weight and egg production (Mwangi *et al.*, 2023). Similarly, Nigerian researchers have adopted low-cost SNP panels for examining growth-related genes in local chicken breeds (Igwe *et al.*, 2022). However, FUNAAB Alpha chickens remain lowly represented in this set of studies, this limits an in depths knowledge into how GH mRNA variability influences their growth trajectories. By integrating molecular genetics with traditional breeding metrics, this research advances Nigeria's poultry sector toward precision agriculture, ensuring genetic gains without compromising the adaptive traits vital for tropical smallholder systems (Adeleke and Ojedapo, 2023). However this study aimed to investigate the genetic variation of GH mRNA in FUNAAB Alpha chickens breed in Uyo, Nigeria. The outcomes will inform national policies on poultry genetic resource conservation while equipping farmers with genetically optimized stocks to boost food security in the country.

1. METHODOLOGY

1.1 Experimental site

The study was conducted at the Poultry Breeding Unit of the Teaching and Research Farm of the University of Uyo, Uyo. Uyo is situated in Akwa Ibom State, the South Southern region of Nigeria found within latitude 4°31'N and 4°50'N, and longitude 7°31'E and 4°50'W. The area is characterized by a tropical humid climate with two distinct seasons: dry and wet seasons. It has an annual precipitation of almost 1000 mm, with only three months considerably low rainfall, from December to February, and little variability in temperature. Its elevation is approximately 38 meters above sea level, relative humidity of 79%, and an average temperature of 28°C (University of Uyo Meteorology Unit, 2024).

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1.2 Experimental animals

A total of 100 day old chicks, 100 FUNAA/B Alpha of 50 male and 50 female were purchased from the Federal University of Agriculture, Abeokuta, Ogun State.

Housing and management of experimental animals

All the birds were raised under the same intensive management system but partitioned into different pens according to their breed. The brooding pen was constructed with dimensions of 30cm in width and 50cm in length. These measurements ensured that each pen house 5 chicks during the entire 8 week of experimental period. One week before the arrival of the chicks, the brooding pen underwent washing, disinfection, cleaning, and fumigation. Beddings made of wood shavings up to 5cm in depth were laid and were changed weekly. Installations and testing of heating sources (electricity and lamps) were done. Furthermore, measures were taken to ensure adequate ventilation and lighting in the brooding pen. Drinkers and feeders were washed, disinfected, rinsed, and dried before usage. On the arrival, the chicks were given glucose incorporated in water to boost their energy level, they were also vaccinated against Newcastle disease. The chicks were winged-tagged for easy identification before they were placed in their allotted pens. The chicks were brood for 3 weeks and starter ration (22% Crude Protein and 2900 Kcal/Kg Metabolizable energy) was given with clean water *ad libitum* on the 4th week birds were transferred to the rearing pen and grouped according to breed and sex, finishers feed (19.41% Crude Protein and 3200 Kcal/Kg Metabolizable energy) were given to the birds till termination period of 8 weeks.

Vaccination

Indigenous Local chickens are resistant to certain diseases of poultry owing to the immunological via water at strength gotten from parents. Anti-stress was administered via water on their arrival at day one. At day one, I/O (Intraocular vaccine) was administered against Newcastle disease, then gumboro vaccine was given at 3 weeks to fight viral diseases. Antibiotics like Antiviral, Coccidiostat (Embazin and Coccifor) were administered through water to prevent Coccidiosis.

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1.3 Data Collection

Growth Data

On arrival the chicks' initial body weight (BW) was measured using SF-400 sensitive scale (with 10000×10g/35oz×0.1oz capacity) before providing them with feed and water. Canny electronic weighing scale (with a maximum capacity of 150kg) as used after the brooding period. This was done weekly for 8 weeks of the research. Linear body parameters were also taken weekly with 150 cm (60inches) maximum tailor's tape. The parameters include: BL, body length (distance from neck joint to the tip of the tail); SL; shank length (distance from the knee joint to the tip phalanges); SC; shank circumference (circumference of the shank at its widest point); BG; breast girth (circumference of the chest at the widest part); KL; keel length (distance from the base of the breast to the end of the sternum); DS; drumstick length (distance from the hook joint to the end of the knee); DC; drumstick circumference (circumference of the drumstick at its widest point) and WL wing length (from the shoulder joint to the tip of the wing).

1.4. Genomics Data

Tissue Harvesting

A total of 16 chickens, comprising of 8 males and 8 females from the population of FUNAAB Alpha chickens were randomly selected for tissue harvesting at 8 weeks to harvest one established growth tissue (liver) for gene expression profiling of Chicken Growth Hormone (GH) gene. The selected chickens were slaughtered liver was quickly cut a smaller piece of the liver with disposable surgical scalpel and immediately dropped into a well labelled Eppendorf tube containing RNA/DNA shield to avoid RNA degradation were stored in an ice box with a temperature of -4°C and taken to the subunit of the Inqaba biotec™ at Ibadan for RNA extraction and qPCR amplification.

RNA Extraction

Following the manufacturer's protocol, an animal tissue RNA purification kit (Zymo Research Quick-RNA MiniPrep Plus Kit) was used to extract the total RNA from tissue sample of liver.

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In preparation for the extraction, the RNA wash buffer was prepared by mixing 48 mls of RNA wash buffer concentrate with 208 (ml) of 95% ethanol. Lyophilized DNase 1 was reconstituted in RNase-free water by gently vortexing 250U with 275 μ l DNase/RNase-free water and was then placed on ice. Lyophilised Proteinase K was immediately placed on ice after being reconstituted at a concentration of 20 mg/ml using 1.04 ml of Proteinase K storage buffer. DNA/RNA shield (2 \times concentrate) and Nuclease-free water at 1:1 ratio to make a 1 \times solution. Four fundamental steps were followed in performing the RNA isolation which include: Sample Homogenization and lysis, Cell lysis, sample clearing, and gDNA elimination, DNase 1 Treatment, and only Purification and elution of total RNA.

Sample lysis (Disruption) and homogenization of Tissue Samples

Efficient disruption of the starting materials (liver tissues) was achieved using RNase-free mortar and pestle. The RNase-free mortar and pestle was pre-chilled in liquid nitrogen. The frozen and preserved tissues were thawed, weighed (25mg) and ground in 500 μ l of RNA shield.

Cell lysis, sample clearing and gDNA removal

After adding 15 μ l of the reconstituted proteinase K and 30 μ l of PK digestion buffer, the samples were vortexed quickly. After that, samples were incubated for 30 minutes at 20 - 30°C. Samples were centrifuged for 30 seconds at 16,000 rpm to eliminate particle matter from homogenized tissue, and the resulting supernatants were then moved into a tube devoid of nuclease. To ensure adequate mixing, RNA lysis buffer was added to the supernatant at a 1:1 ratio and vortexed. To eliminate most of the genomic DNA, samples lysed in RNA lysis solution were put onto a yellow Spin-away filter and centrifuged. The flow-through was retained in situ and 95-100% ethanol was added to it after which it was vortexed for proper mixing. The samples were then transferred into the Zymo-Spin III G column (green) in a collection tube and centrifuged. Flow-through was discarded and green collection tubes were transferred into well labelled nuclease-free tubes.

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DNase I treatment

The green column was centrifuged after being washed with 400 μ l of RNA wash buffer. Flow through was thrown away. 75 μ l DNA digestion buffer and 5 μ l DNase 1 (1U/ μ l) were thoroughly mixed together and added into the column matrix, it was then incubated for 15 minutes at 20-30°C.

Total RNA purification and elution

400 μ l RNA prep buffer was added to the column and centrifuged and flow-through discarded. 700 μ l RNA wash buffer was added to the column and centrifuged and flow-through discarded. 400 μ l RNA wash buffer was added again to the column and centrifuged for 1 minute to ensure complete removal of the wash buffer. Column containing RNA was transferred into a nuclease-free tube. After adding 50 μ l of DNase/RNase-Free water to the column matrix, it was centrifuged for one minute at 16,000 x g. To ensure optimal elution, this procedure was carried out twice.

RNA purity and concentrations check of cGH gene

The Nano-drop spectrophotometer was used to measure the concentration and purity of the RNA samples. After using lint-free tissue to gently clean and buff the pedestals, 2 μ l of blanking solution (Nuclease Free Water) were put onto each pedestal, and the blank measured. Following the measurement of the blank, the pedestal was cleaned, and 2 μ l of RNA sample were put onto it. The optical density ratios of 260/280nm and 260/230nm were then determined for each sample. The ideal 260/280nm value is (geq 1.70). The 260/280nm ratio indicates the extent to which samples are free from contaminating protein. Protein contamination is indicated by values below 1.70. A sample's purity from salts and other impurities can be determined using the 260/230nm ratio. Values (geq 2.0) is the ideal 260/230nm value, less than 2.0 values suggest the presence of contaminants (Desjaldings and Conklin, 2010).

Reverse transcription (cDNA synthesis)

Reverse transcription reaction of the RNA samples using primer for cGH gene was performed by converting only the RNA nucleotides that corresponded to protein-encoding genes into complementary DNA (cDNA).

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As a fraction of total cellular RNA from liver, messenger RNA (mRNA) which is the RNA that codes for the protein sequence, was isolated and purified. With the aid of an RNA-dependent DNA polymerase enzyme known as reverse-transcriptase, mRNA was converted into a cDNA template during the reverse-transcription process. Reverse transcription (RT) was performed using the LumScript RT Super Mix Kit in accordance with the manufacturer's convention. The RT was performed on the extracted tissue sample as indicated in Tables 2.1 and 2.2.

Table 2.1: LumScript RT Supermix kit Reaction Methodology for cDNA Synthesis

Components	Per 20µl RXN	Final concentration
LumScript RT SuperMix (5×)	4µL	1×
RNA sample	1µL	(up to 1 µg)
Nuclease-free water	15µL	

Table 2.2: cDNA Synthesis Incubation Steps

Step	Temperature	Time
Primer annealing	25°C	2 minutes
cDNA synthesis	55°C	10 minutes
Heat inactivation	95°C	1 minute

Primer Design for PCR Amplification

Primers were designed and were used to amplify the GH gene and housekeeping gene (GAPDH gene). The sequences of the primers for the amplification are presented in Table 2.3.

Table 2.3: cGH and GAPDH primer sequences

Product Name	Sequence of Forward (F) and Reverse (R) Primers
cGH (F):	(5' TCCCAGGCTGCGTTTTGTTACTC ATCCCCAGGCAAACACCCTC-3')
(R):	(5'ACGGGGGTGAGCCAGGACTG CCTCGACATCCAGCTCACAT-3')
GAPDH (F):	(5'-GAGAAATTGTGCGTGACATCA-3')
(R):	(5'-CCTGAACCTCTCATTGCCA-3')
(Kumar <i>et al.</i> , 2020)	

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qPCR Reaction of cGH gene

Quantitation of reverse transcription product (cDNA) for the GH gene was done using Luna Universal qPCR master mix. The qPCR reaction was also prepared according to manufacturer's instruction as stated in tables 3.4 and 3.5. The Bio Rad CFX96 Real-time thermal Cycler was used to run the qPCR reaction. The critical result was the final quantity of Amplicon produced after the process which was read following fluorescent detection in the Real-time mainline. The RT-PCR uses the linearity of DNA amplification to determine absolute or relative amounts of a known sequence in a sample. By using a fluorescent reporter in the reaction, the amplicons were detected.

Table 2.4: qPCR Protocol of Luna Universal qPCR Master Mix

Components	20 μ l reaction	Final concentration
Luna universal qPCR mix	10 μ l	1 \times
Forward primer (10 μ M)	0.5 μ l	0.25
Reverse primer (10 μ M)	0.5 μ l	0.25
Template DNA	1 μ l	<100ng
Nuclease free water	8 μ l	

Table 2.5: Real-Time qPCR (RT-qPCR) incubation steps

Cycle Step	Temperature	Time	Cycles
Initial denaturation	95°C	60 Secs	1
Denaturation	95°C	15 Secs	40 \pm 5
Annealing/Extension	60°C	30 secs	(+plate read)
Melt curve	60-95°C	Varied	1

Bioinformatics analysis

After sequencing of cGH mRNA, the sequences were viewed in Bioedit and BLAST against GenBank at the National Centre for Biotechnology Information, U.S. This was done to check quality and similarity of the sequences with cGH sequences from other breeds of chicken. The sequences were trimmed and filtered for quality control before identification of single nucleotide polymorphism.

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Reference sequence of cGH gene was downloaded and aligned against GH sequences from this study to identify single nucleotide polymorphism presence among the sequences. The sequences were submitted to Genbank and accession numbers were given as: PV392654, PV392665, PV392656, PV392657 PV392658, PV392659, PV392660 PV392661 (Udoh *et al.*, 2025). The frequency and distribution of the identified single nucleotide polymorphisms were estimated using DNAsp software. Genetic diversity indices of the sequences were estimated using R software. The single nucleotide polymorphisms identified were used in variant prediction effect using ENSEMBL. The sequences were translated to protein sequences.

1.5 Statistical Analysis

Descriptive statistics

Descriptive statistics, including measures like mean, median, standard deviation, and range, was computed to summarize the characteristics of the experimental data. All data collected on growth performance traits were presented as means \pm SEM (standard error of the mean).

Association analysis

After a preliminary analysis of 2 by 2 factorial experiments to account for effects of sex, breed and SNPs and their interactions on growth performance traits, interaction effects (First and Second levels) were not significant. The data were then subjected to three-way analysis of variance using the Generalized Linear Model procedure of Statistical Analysis System (2000). Differences between means was determined using Least square means (General Linear Model Procedure) and Duncan's multiple range tests (Duncan 1955) as a post hoc test at a significance level of 0.001. The statistical Model used was:

$$Y_{ijkl} = \mu + B_i + S_j + S_k + e_{ijkl}$$

Where:

Y_{ijkl} is the individual observed trait,

μ = population mean,

B_i = the fixed effect of the breed (2- FUNAAB Alpha and Ross 308),

S_j = the fixed effect of the j th sex (2- male and female)

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S_k = the fixed effect of the k th SNP haplotype (4- Hap. 1, Hap. 2, Hap. 3 and Hap. 4)

e_{ijkl} = the random residual errors.

2. RESULTS AND DISCUSSION

2.1. Characterization of Nucleotide Substitutions and Diversity

The results of the analysis shown in Table 3.1 indicated that the four GH mRNA sequences of Improved Nigerian Indigenous FUNAAB alpha chickens revealed a high conservation pattern of GH gene and low genetic variation at the protein coding region of the gene, with nucleotide diversity (π) of 0.00390, when computed with a Jukes-Cantor corrected value ($\pi(JC)$) of 0.00392. This indicated a very low level of genetic variation within the sampled FUNAAB Alpha chickens population. The results showed a mutation rate estimates (Theta (θ)) which is a measure of the population mutation rate and was consistently estimated to be 0.00425 across the three different methods (Eta, S, and Pi) used in this study. The closeness of the values experienced in these two methods π and θ showed the agreement between them which suggests a stable population history for this gene without evidence of recent drift.

For mutation occurrence the estimated transition/transversion bias (R) was 1.37. This value indicated that transitions (mutations between purines, A \leftrightarrow G, or between pyrimidines, C \leftrightarrow T) occurred more frequently than transversions (purine to pyrimidine or vice versa) mutation.

The very low values for π and θ are characteristics of a highly conserved protein-coding gene under strong purifying selection or drift. Growth hormone is a critical protein for growth and metabolism, and non-synonymous mutations that altered its amino acid sequence which are likely to be deleterious and thus removed from the population by natural selection. This results in a gene sequence that changes very slowly over time.

This result also corroborated with the report by oluwaseum (2022) who observed that the GH gene in a different Nigerian indigenous chickens ecotype was highly conserved, reporting a similar low nucleotide diversity ($\pi < 0.005$).

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This consistency report of similar results across studies on local Nigerian breeds suggests a common evolutionary history where strong functional constraints on the Growth hormone protein lead to minimal sequence variation.

The transition/transversion bias ($R = 1.37$) is a common biological phenomenon. Transitions are biochemically more probable than transversions due to the similar chemical structures of the bases involved (A and G; both are purines). This result confirms that the observed mutations followed expected molecular evolutionary patterns and are not random. However, these findings aligns with the observation of Chen *et al.* (2020) who reported a transition/transversion bias to range between 1.2 to 2.0 for typical vertebrate protein coding genes, reflecting the underlying biochemical mechanisms that favour transitions over transversions in their large meta-analysis of substitution pattern in vertebrate mitochondrial and nuclear genomes providing a large comparative framework.

Table 3.1: Genetic diversity indices of GH mRNA of FUNAAB alpha chickens

Genetic diversity Statistic	Value	Interpretation
Nucleotide diversity (π)	0.00390	Low diversity, indicating high conservation across sequences
Jukes-Cantor corrected π	0.00392	Very similar to raw π , suggesting minimal effect of multiple hits
Theta (θ) per site (from Eta, S, Pi)	0.00425–0.00428	Estimates of mutation rate per site; consistent across methods
Average pairwise differences (k)	1.5	On average, 1.5 nucleotide differences between sequence pairs
Transition/Transversion ratio (R)	1.37	Transitions slightly more common than transversions (expected)

2.2 Determination of Sequence Conservation and Pairwise Distances of GHgene of FUNAAB alpha chickens

The result of the analysis compared the sequences of GH mRNA of FUNAAB alpha chickens which provides a clear understanding of the relationships between individual birds studied as presented in Table 3.2.

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In considering pairwise distance Matrix; The analysis showed that three of the four sequences (PV392654_F35C, PV392655_F30C, and PV392656_F37C) were identical with zero distance ($d= 0$) while the fourth sequence, PV392657_F39C, differed from others by a genetic distance of 0.01, Table 3.3.

For base composition the overall base composition was remarkably uniform and balanced across all the four sequences, with each nucleotide (A, T, C, G) constituting approximately 25% of the sequence. PV392657_F39C showed a very minor shift, with a slight decrease in C (29.1% vs. 29.9%) and a slight increase in G (26.2% vs. 25.7%) contents. The pairwise distance results directly explain the diversity indices. The fact that 3 out of 4 sequences are identical means the population sample is dominated by a single major haplotype. The present of single divergent sequence (PV392657_F39C) is responsible for the entire measured nucleotide diversity ($\pi = 0.0039$) and the average number of pairwise differences ($k = 1.5$) as presented in Table 3.4 and Table 3.5.

The finding of this study does not agree with the observation of Hassan *et al.*, 2021 which reported on a commercial broiler line of a higher number of distinct haplotypes and greater average pairwise distance within their population, indicating a quantitative higher level of polymorphism at the GH locus compared to those of FUNAAB alpha breed. This discrepancy reflects evolutionary trajectories hence, could be attributed to the different breeding histories as commercial lines are often derived from crosses of multiple, diverse founder populations, whereas the FUNAAB Alpha breed as a stabilized local breed, may have originated from a narrow genetic base which passed through a genetic bottleneck during its formation, leading to reduced diversity. The observed pattern of one dominant haplotype and one variant is a genetic signature of such a demographic event.

The highly uniform base composition suggests no strong mutational bias (e.g., GC-content bias) acting on the GH mRNA of FUNAAB alpha population. The minor deviation in the PV392657_F39C sequence is consistent with it being a unique, low frequency variant in which the defined mutation affect the nucleotide counts but does not affect genome or specific gene.

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Table 3.2 Pairwise distance among the sequences in GH mRNA of FUNAAB alpha Chickens

PV392655_F30C	PV392656_F37C	PV392657_F39C	PV392654_F35C
PV392656_F37C	0		
PV392657_F39C	0.01	0.01	
PV392654_F35C	0	0	0.01

Table 3.3 Sequence conservation among the sequences in GH mRNA of FUNAAB alpha Chickens

	T(U)	C	A	G	Total
PV392654_F35C	19	29.9	25.5	25.7	385
PV392655_F30C	19	29.9	25.5	25.7	385
PV392656_F37C	19	29.9	25.5	25.7	385
PV392657_F39C	19	29.1	25.7	26.2	385

U- Uracil, T- Thymine, C- cytosine, A- Adenine, G- Guanine

Table 3.4 Pairwise Distance Matrix in GH mRNA of FUNAAB alpha Chickens

Sequence Pairs	Genetic distance
All vs PV392654_F35C or PV392655_F30C	0
PV392656_F37C vs PV392657_F39C	0.01
PV392657_F39C vs others	0.01

Table 3.5: Base Composition in GH mRNA of FUNAAB alpha Chickens

Base	Avg. Frequency (%)	Conservation
A, T, C, G	~25% each	Uniform distribution
PV392657_F39C shows minor shift: ↑G (26.2%), ↓C (29.1%)	Slight composition change only	

U- Uracil, T- Thymine, C- cytosine, A- Adenine, G- Guanine

2.3 Phylogenetic Analysis of GH mRNA Sequences in GH mRNA of FUNAAB alpha Chickens

The evolutionary relationships among the sequences in GH mRNA of FUNAAB alpha Chickens were visualized using a Neighbor-Joining Phylogenetic tree, Fig 3.1

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In considering the phylogenetic tree constructed from the 448 bp-
position sequences alignment showed a very short sum of branch lengths
(1.210), confirming the low overall divergence. The branching pattern of
phylogenetic tree showed three sequences (PV392654_F35C,
PV392655_F30C, PV392656_F37C) forming a single clade or cluster with
zero branch lengths between them, indicating that they were of the same
haplotype. The sequence PV392657_F39C connected to the main cluster by a
very short branch, representing its genetic distance of 0.01.

The phylogenetic tree provides a visual confirmation of the results from
Tables 3.1 and 3.2. It clearly demonstrates that the genetic variation within this
FUNAAB Alpha sample is low which is primarily driven by this single rare
variant seen. The tight clustering of the sequences reflects the high degree of
conservation of the GH gene.

The result obtained in this study agrees with the phylogenetic findings of
Udoh (2023), where sequences from Nigerian indigenous chicken population
formed tight, low diversity clades. Both studies depict a phylogenetic structure
dominated by a major haplotype with very short branches connecting minor
variants, reinforcing the model of a conserved gene in a relatively homogeneous
population. The outlier sequence (PV392657_F39C) likely represents a recent,
low-frequency mutation within the population. This is a common finding in
genetic studies of domesticated animals, where a population may be largely
homogeneous but still contain rare polymorphisms. The result of this study
agrees with the phylogenetic findings of Adebayo *et al.* (2021) where sequences
from Nigerian indigenous chicken populations formed tight, low-diversity
clades with very short internal and external branches for the GH gene in their
research on the survey of candidate genes in local ecotypes of chickens. The
result obtained in this study agrees with the observation of Adebayo *et al.*
(2021) who reported that a single haplotype was found dominating the entire
star-like topology in their phylogenetic studies of Nigerian chicken ecotypes.
This however depicts a phylogenetic structure that emphasized GH gene to be
more conserved even in homogeneous population.

CONCLUSION

In conclusion the GH mRNA is highly conserved within the sampled FUNAAB Alpha population, as evidenced by very low nucleotide diversity ($\pi \approx 0.0039$) and the presence of a single dominant haplotype in 75% of the samples. The genetic variation that does exist is minimal. It is characterized by a low transition/transversion ratio (1.37) and is largely attributable to a single divergent sequence (PV392657_F39C). The consistency between different estimators of genetic diversity (π and θ) suggests a stable demographic history for this gene in the FUNAAB Alpha breed, with no signs of a severe genetic drift or recent selective sweep affecting the GH locus. The extreme conservation may be due to strong purifying selection acting on the Growth Hormone gene, as amino acid changes could have significant detrimental effects on growth and development. The FUNAAB Alpha chickens show a very low level of polymorphism in the GH mRNA coding sequence, which is indicative of a genetically stable and uniform population for this gene.

Recommendations

Large Sample Size and Scope should be considered in the future research in order to obtain a more robust estimate of genetic diversity and to accurately determine the frequency of the rare variant (PV392657_F39C) in FUNAAB Alpha population. Analysis should be extended to include the promoter and regulatory regions of the GH gene which might revealed more variations that influence gene expression levels rather than the protein structure.

Genotype and Phenotype data (individual growth rates, feed conversion ratio and body weight) should be correlated to observe any functional consequence in relation to this rare genetic variant (PV392657_F39C). If this variant is a non-synonymous mutation, in silico analysis (SIFT, PolyPhen-2) could be used to predict its functional impact.

Comparative Analysis with Performance Data: A direct comparative study of the GH gene diversity between FUNAAB Alpha and a commercial breed like Ross-308 coupled with actual farm performance data, would be highly valuable. This would determine if differences in GH polymorphism are linked to differences in growth performance between local and commercial breeds.

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Investigate Epigenetic Regulation: Given the high coding sequence conservation, exploring epigenetic modifications (e.g., DNA methylation of the GH promoter) could be a fruitful avenue to understand the regulation of this gene and its potential role in explaining individual variation in growth traits.

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Conflict of interest

We declare that there is no conflict of interest with any financial, personal, or other relationships with other people or organization related to the material discussed in this manuscript.

Ethical Approval

This research was conducted in accordance with ethical guidelines governing the use of animals and genetic materials in scientific research as stipulated by the Ethical Committee of Animal Science, University of Uyo.

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CHAPTER 2
**DATA-DRIVEN OPTIMIZATION OF NUTRIENT
FLOWS IN INTEGRATED CROP–LIVESTOCK
FARMING SYSTEMS USING MACHINE LEARNING**

¹ Fahad AMJAD
² Muhammad ZAIN
³ Warda AMJAD

¹The Islamia University of Bahawalpur, Bahawalpur, Pakistan, fahadamjad778@gmail.com
ORCID ID: 0009-0003-7318-9887

²University of Bonn, Bonn, Germany, s27mzain@uni-bonn.de, ORCID ID: 0009-0007-1912-1557

³The Islamia University of Bahawalpur, Bahawalpur, Pakistan, f24bzool4e01002@iub.edu.pk
ORCID ID: 0009-0007-0345-4445

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INTRODUCTION

The agricultural industry faces a major problem. They have to choose whether to grow sufficient food for an ever-increasing world population or protect the environment where such food grows. By 2050, the world will require 60% more food than in 2010 (Canton, 2021; FAO, 2022). In the face of this challenge, the integration of crops and livestock in farming systems (ICLS) emerges as a very promising approach that may help combine productivity with sustainability through nutrient recycling and minimizing the use of chemicals (Franzluebbbers, 2024).

The management of nutrients plays a crucial role in ensuring agricultural sustainability. The most important macronutrients, nitrogen (N) and phosphorus (P), are essentials for plant growth and livestock feeding. However, the conventional agricultural practices suffer from inherent inefficiencies: roughly half of the nitrogen fertilizers used in the world's crops and grasslands are not absorbed by the plants but instead become environmental pollutants due to leaching, volatilization, and biological breakdown processes (Pan et al., 2022). Such inefficient usage results in eutrophication of surface waters, groundwater pollution, and nitrous oxide (N₂O) emissions, a powerful greenhouse gas with 265 times more global warming potential than CO₂ within a 100-year time frame (Tian et al., 2020).

ICLS addresses these problems by establishing closed nutrient cycles where livestock feeds off agricultural waste and provides nutrients to the soil through manure application and proper grazing management, thus enhancing soil biological and physical characteristics. However, due to the multiplicity of processes involved in such a multifactorial system, including soil biogeochemistry, plant physiology, animal feeding, and microbial communities, traditional nutrient management strategies are not sufficient to handle the task. Soil testing and fertilizer guidelines based on empirical knowledge cannot effectively manage the nutrient dynamics in an ICLS environment (Shanmugam et al., 2024).

Machine learning (ML) holds immense potential in dealing with this complexity.

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Through the use of large, multivariate data sets incorporating information about soil characteristics, meteorology, crop productivity indicators, animal productivity indices, and remote sensing information, machine learning techniques are able to unearth nonlinear correlations and make predictions which cannot be made using conventional agricultural models. The use of random forest, gradient boosting techniques, artificial neural networks, and deep learning techniques has proven successful in predicting soil fertility levels, optimally applying fertilizers, and modeling nutrient cycles (Folorunso et al., 2023; Folorunso et al., 2025).

In spite of all this, however, a thorough conceptual framework for using ML to optimize nutrient flow in integrated crop-livestock systems is not well-developed at present. This chapter aims to bridge this knowledge gap by discussing the theoretical bases of nutrient cycling in ICLS, identifying the constraints associated with current management practices, examining recent advancements in the use of ML techniques for nutrient management, and proposing a new conceptual framework of data-driven optimization of nutrient flows.

1. INTEGRATED CROP–LIVESTOCK FARMING SYSTEMS

1.1 Concept and Importance

The ICLS is an agri-production system characterized by the purposeful arrangement of the crop and livestock farming enterprises in such a way that the byproducts from one of the components act as inputs for the other component. In ICLS, the livestock utilizes the biomass from the plants that are not suitable for consumption by humans and uses them to produce high-value proteins and energy while providing manure for the crops (Lou et al., 2025). The design provides an opportunity for closing loops of nutrients that could have been open in specialized systems.

ICLS hold significance in ecological, economic, and social terms. Ecologically, they enhance biological diversity via crop rotation and habitat diversification, increase the amount of soil organic matter via manure application and the contribution of pasture roots, and decrease the agricultural sector's ecological impact by minimizing the use of chemical fertilizers and

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pesticides (Franzluebbers, 2024). Economically, ICLS ensure that the farm has different revenue sources, lower expenses, and act as a buffer for any potential market or climatic changes. Socially, ICLS support subsistence farmers in South Asia, sub-Saharan Africa, and Latin America, where mixed crop-livestock farming is still the prevailing production method (Shanmugam et al., 2024).

ICLS is acknowledged by FAO to be a key component of climate-smart agriculture with potential to mitigate GHG emissions and enhance carbon sequestration in addition to boosting adaptation capacity against climatic changes (FAO, 2022). Numerous pieces of evidence from field studies show that ICLS within carefully designed grazing management practices and manure recycling can help achieve comparable yields with lower external nutrients supply than specialist crops by up to 20-40% (Franzluebbers, 2024).

1.2 Role in Sustainable Agriculture

The concept of sustainable development presents ICLS as an approach to production intensification that is based on harmony with, instead of opposition to, nature. Since ICLS rely on the closure of nutrient cycles, these systems reduce the risk of non-point source contamination of watercourses by agricultural activities – the most significant reason for eutrophication of freshwaters worldwide (Liu et al., 2024). The introduction of animals into crop production has been shown to result in higher soil organic carbon content, increased aggregate stability, higher infiltration rates, and more intensive microbial activity (Du et al. 2022).

ICLS are involved in the process of mitigation of climate change as well. Through replacing nitrogen fertilizer use which is responsible for 1-2% of the total world energy consumption and causes substantial amounts of N₂O emissions with biological nitrogen that can be supplied by using legumes and livestock together along with returning manure, ICLS may lower the carbon footprint associated with food production (Tian et al., 2020). Furthermore, perennials used for foraging in ICLS systems contribute to carbon storage in soils, thus creating negative emissions from agriculture (Franzluebbers, 2024).

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Goals of sustainability with ICLS need to be carefully weighed. Overgrazing can impair soil structure, promote erosion, and undo all the good that the integration of crops and livestock is doing by improving soil quality. Nutrient requirements may be surpassed through manure application, resulting in a buildup of phosphorus in soils and high levels of N₂O emissions. The scaling up of such practices at an agricultural landscape level demands nutrient flow management between the crops and livestock farmers at the regional scale.

2. NUTRIENT CYCLING IN INTEGRATED FARMING SYSTEMS

2.1 Nitrogen and Phosphorus Dynamics

Nitrogen and phosphorus are the key macronutrients that drive agriculture, and the cycling of nitrogen within ICLS requires a detailed series of biological, chemical, and physical processes. The major sources of nitrogen include synthetic fertilizers, Biological Nitrogen Fixation (BNF) from legumes, atmospheric deposition, and manure. Once incorporated into the soils, N will be immobilized into microorganisms, mineralized to ammonium (NH₄⁺), nitrified to nitrate (NO₃⁻), and lost via denitrification, leaching, and ammonia emission. In ICLS, the inclusion of multiple plant species, including legumes, and animal manure alters the scale and direction of N cycling from those in monocultures.

Numerous studies have shown that the presence of livestock hastens N cycling through excretion of considerable amounts of N-rich materials that are easily mineralized. The high concentration of N in urine spots facilitates nitrification and denitrification leading to local emissions of N₂O that can be twice to five times higher than that of the background levels of soil emissions (Tian et al., 2020). Nevertheless, ICLS generally show a decreased rate of N loss per unit of food produced due to internal circulation of N as opposed to exporting N in synthetic fertilizers (Liu et al., 2024).

The behavior of phosphorus within ICLS systems is influenced by the use of livestock manures as well as by the incorporation of crop residues, but in a much lower degree compared to that of nitrogen. Phosphorus does not possess any gaseous form of transport through the atmosphere and, therefore, its major environmental loss is through surface runoff.

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The reason for this is that livestock manure possesses a high level of phosphorus since the amount consumed by animals surpasses the requirements for their metabolic processes. For instance, the concentration of phosphorus in the excrement of cattle is between 1.5 and 4.0 kg P₂O₅ per ton (Sutton et al., 2013).

2.2 Role of Maize Fodder in Nutrient Flow

Maize (*Zea mays L.*) plays a crucial role in numerous integrated crop-livestock systems, serving as both a cereal crop for consumption by humans and animals and a productive forage crop that provides green or preserved forage for animal feeding. Being a highly nutritional crop, maize absorbs large amounts of N, phosphorus (P), and potassium (K) from the soil; thus, when producing 8 Mg per hectare, maize uses up to 120-150 kg per hectare of N, 40-60 kg per hectare of P₂O₅, and 60-80 kg per hectare of K₂O (Essilfie et al., 2024). In case when maize is grown for fodder use, the removal of the total biomass will contribute to even larger losses of nutrients from the soil that need to be restored.

Therefore, the use of maize fodder in the nutrient cycle of ICLS is two-way. In terms of crops, it results in increased nutrient needs which are, at least partly, supplied by animal manure derived from previous production seasons. On the livestock side, maize silage and green chop are sources of high-energy and easily digestible food that enables the production of milk and meat, and whose residue in the form of manure serves as nutrient-rich substrate returned to the soil. Several studies conducted on the Chinese wheat-maize cropping systems have confirmed that using animal manure instead of synthetic nitrogen improves soil carbon levels, increases microbial richness, and increases SYI indices without reducing grain yields (Li et al., 2023).

However, the nutritional value of maize fodder determines the composition of the manure itself, depending on whether cattle are fed high-energy diets or pastures. This makes it necessary to collect comprehensive data on both crop and livestock nutrition in order to determine the impact of one upon another.

2.3 Livestock Manure Recycling

Livestock manure acts as the essential element that connects the two farming subsystems, livestock and crops, within the framework of sustainable integrated farming systems. The chemical structure, physical nature, and microbiological community of manure create an invaluable organic substance that facilitates the enhancement of soil fertility and crop productivity.

Fresh cattle dung usually have about 0.30-0.45% nitrogen (N), 0.15-0.25% phosphorous (P), and 0.10-0.15% potassium (K) in terms of fresh weight, in addition to the presence of large amounts of organic content that contribute to the formation of soil carbon reserves. On the other hand, poultry manure is much richer in nutrients and has a nitrogen level of 3.0-5.0% and a phosphorous level of 1.0-2.0%, with a smaller C:N ratio (Agbede, 2025).

The availability of nutrients for the crops in the initial year is based on mineralization, which, in turn, depends on the C:N ratio of the manure, soil temperature, soil moisture, and activity of soil microbes. Fresh manure tends to make available more accessible nutrients for the crops since it contains high amounts of minerals and materials that could be easily converted into minerals. Although composted manure takes longer to release nutrients, it helps improve the quality of soil organic matter, increase diversity of microbes in the soil, and promote better soil quality. Therefore, the selection between using fresh manure or its compost and appropriate fertilization techniques are important when trying to enhance NUE while reducing fertilizer losses through leaching, runoff, and volatilization (Denoncourt et al., 2025).

Digital innovations and artificial intelligence are driving developments in circular manure management. The use of decision support systems that include live data on the nutrient composition of manure, soil fertility conditions, nutrient needs of crops, and weather predictions has been embraced. This is an application of data-enabled nutrient management practices that lead to efficient recovery and utilization of animal waste, minimal environmental pollution, and higher profits for farmers (Oyedun et al., 2025).

2.4 Soil Fertility and Nutrient Balance

ILCS fertility sustainability depends on the ratio of nutrient addition through various sources (manures, fertilizers, BNF, atmospheric deposition) and nutrient removal (crop removal, leaching, gas emissions). It is crucial to maintain nutrient balance either positive or neutral in order to achieve sustainable productivity levels while preserving soil natural fertility potential. Fertilizer experimentation over time shows that the use of combined organic and mineral fertilization is more efficient than applying each method independently in terms of soil organic matter accumulation, yield stability, and microbial communities (Xing et al., 2025).

Soil organic matter is the key indicator of soil health in ICLS. Soil organic matter increase is achieved due to crop residue and manure, serving as the source of carbon available for decomposition and humic substance formation by microorganisms. The research carried out in the ICLS system of crop rotation showed that using combined organic and mineral fertilization increased enzyme activity, including invertase by 51.9%, urease by 38.3%, and cellulase by 122.4%. The mentioned results demonstrate the improvement of nutrient cycling capability (Xing et al., 2025). It is evident that an improvement in biological activity is associated with yield increase.

A major issue in ensuring the nutrient balance of the soils in ICLS is nutrient heterogeneity. This is caused by the uneven deposit of manure in pastures and fields due to livestock grazing. Additionally, the spatio-temporal variations of nutrients owing to seasonal changes, plant life cycle, and the movement of animals require a real-time approach, which cannot be achieved using conventional fertilizer application strategies. A data-oriented approach is one way of handling these issues, as discussed in the next sections.

3. CHALLENGES IN CONVENTIONAL NUTRIENT MANAGEMENT

3.1 Nutrient Losses and Inefficiencies

The traditional management of nutrients in agriculture, whether crops or animals, is filled with inefficiencies that exist along many different pathways. On a global level, the nitrogen use efficiency of crops (NUE) has been estimated at only 40-60%, implying that 40-60% of applied nitrogen is wasted and is not

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assimilated by the plants (Liu et al., 2024). This waste is achieved through leaching losses, either through nitrates entering the ground or surface waters, or ammonia losses through volatilization from animal manure and synthetic nitrogenous fertilizer, such as urea (Tian et al., 2020). Inefficiencies are not only associated with nitrogen but with phosphorus as well. Only 20% of mined phosphorous ends up in the human food chain, with the remainder ending up in soils, erosion from the soil into watersheds, or trapped in insoluble forms within the soil (Sutton et al., 2013).

On a field level, farmers using nitrogen fertilizers without knowing the exact soil N availability and crop absorption rate along with current weather conditions end up applying an excess amount of fertilizer as a protective measure, leading to further loss and environmental issues. The research carried out on dryland farming has indicated that prolonged excessive application of fertilizer leads to excess soil nitrogen and phosphorus being leached and washed away by precipitation into the groundwater and surface water bodies, posing environmental threats (Liu et al., 2024). As much as 50% of nitrogen fertilizer used in agriculture is lost into the environment through processes such as nitrates leaching, ammonia volatilization, and N_2O release (Pan et al., 2022).

3.2 Environmental Impacts

Consequences of improper nutrient management in conventional agriculture systems are far-reaching. Nitrogen runoff causes the problem of eutrophication of fresh water and marine ecosystems resulting in dead zones, harmful algal blooms, and reduction of aquatic biodiversity. Anthropogenic nitrous oxide emissions, emitted through the process of nitrification and denitrification caused by fertilizers application to the soil, account for roughly 60-70% of all anthropogenic emissions of this strong greenhouse gas. Thus, agriculture is the primary source of N_2O emissions. Moreover, its long lifespan of about 114 years makes contemporary emissions a factor of global warming for the next hundred years (Tian et al., 2020).

Eutrophication of fresh water bodies is caused by increased phosphate runoff from agricultural lands into streams. Despite the fact that it was known for decades, phosphate concentrations in the streams have only increased (Singh et al., 2023).

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Management of conventional livestock production creates a concentration of pollutants, which results in an increased chance of water contamination. Animal husbandry industry accounts for approximately 80-90% of anthropogenic ammonia emissions. Integrated nutrient management, which includes measures that help decrease ammonia emission during manure management, can bring great improvements to the environmental situation (Tian et al., 2020).

Apart from nitrogen and phosphorus, the conventional agricultural process that does not include the integration of ICLS causes depletion of soil organic matter, hence diminishing soil buffer ability against nutrient losses. Soil with low soil organic matter has less cation exchange capability, retains less water, and contains less microbial life, leading to increased nutrient leaching when fertilizers are added to the soil. This is an ongoing negative cycle that can be broken using data analysis and decision support tools.

3.3 Limitations of Traditional Farming Practices

Traditional nutrient management practices, based on averages of fertilizer rates calculated from regional soil surveys, fixed fertilization timings, and general crop nutrient needs, fail miserably to match the spatiotemporal variation inherent in nutrient dynamics in ICLS. Nutrient concentrations in the soils may differ significantly, ranging up to several orders of magnitude, depending on topography, soil texture, history of crops grown, and distribution pattern of manures deposited through the activity of grazing animals. Applying fixed-rate fertilizer recommendations across heterogeneous fields will invariably lead to under fertilization in low-nutrient areas and overfertilization in high-nutrient areas.

The issue of temporality complicates the problem of nutrient management even more. Nutrient needs of crops change with time, and nutrients in organic matter, such as manure, are released through mineralization processes, which depend on temperature and moisture, changing daily or weekly. Fixed amounts of nutrients recommended to be added in advance or during growth periods will not correspond to the needs of crops and lead to the early mentioned consequences.

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Moreover, the intricate relationship dynamics among the soil, plant, animal, and microbial elements within the ICLS will result in behaviors that are too complex for humans to optimize based on their understanding alone. This complexity stems from the dependency of manure quality, microbial activity in the soil, nutrient assimilation in plants, feed efficiency in animals, and weather conditions, all of which combine to form a high-dimensional decision space. Such decision spaces are beyond the capability of traditional agricultural methodologies to handle, whereas machine learning models can excel in these settings.

4. MACHINE LEARNING IN AGRICULTURE

4.1 Overview of Machine Learning Techniques

Machine learning is a large collection of algorithms that are capable of learning relationships and patterns from data without any explicit programming. With respect to the application of nutrient management in agriculture, there are several types of machine learning algorithms which can be effectively applied. Supervised learning algorithms such as RF, SVM, gradient boosting techniques like XGBoost and LightGBM, and artificial neural networks (ANN) are trained on labeled datasets to make predictions about target variables such as nutrient concentration in the soil, crop yields, or the optimal quantity of fertilizers. Unsupervised learning algorithms, such as k-means clustering and self-organizing maps, are used for the identification of patterns within soil and crop data without any pre-defined classes. Deep learning models, such as CNN and LSTM, can extract hierarchies of features from complicated sources of data, including satellite imagery, hyperspectral reflectance, and time-series records of sensors (Folorunso et al., 2025).

According to the systematic survey of ML approaches used in soil nutrient prediction by Folorunso (2025), random forest and gradient boosting algorithms were superior to all others in the prediction of soil macronutrients using spectroscopic, satellite imagery, and multimodal sensor data, with prediction efficiency ranging between $R^2 = 0.75$ and $R^2 = 0.95$ for prediction of soil nitrogen, phosphorus, and potassium levels in various soils.

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Artificial neural networks could predict soil pH and calcium levels accurately with large enough datasets used for training, and support vector machines proved to be efficient algorithms for high-dimensional hyperspectral reflectance data analysis (Folorunso et al., 2025).

Feature engineering, which is another critical yet often overlooked component in developing machine learning models for nutrient management, involves selecting and transforming the right input variables such that they are highly relevant to the output target. Features that would be important in an ICLS include those pertaining to soil physics/chemistry, vegetation indices, meteorological variables, animal production information, and management history. Successful feature engineering depends on having agri-related domain expertise that can determine which variables have direct causal relations with nutrient cycling processes, and applying statistical techniques to filter out irrelevant variables.

4.2 Applications in Crop and Livestock Systems

The use of ML in agriculture has seen a tremendous increase in the last decade, thanks to the explosion of Internet of Things (IoT) sensors, UAVs, and satellite data that provide the necessary large dataset to develop predictive algorithms. ML algorithms have found applications in predicting soil nutrient content using remote sensing imagery, crop yield prediction, irrigation schedule optimization, and nutrient deficiency symptom detection from digital images in agricultural crops (Folorunso et al., 2025; Senapaty et al., 2023).

ML-based systems that leverage real-time data from sensors planted in the soil along with agricultural and weather data show significant potential in providing solutions for precision fertilization. A multisensory ML-based solution with the combination of NPK, pH, temperature, and weather sensors processed via Random Forest and Gradient Boosting algorithms reached accuracies in crop recommendation between 95.8% and 99.3% for 22 crops in a controlled experiment in Bangladesh, with the best-performing algorithm running on edge hardware for real-time crop recommendation (Sharafat et al., 2025).

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Similar ML solutions with algorithms including LightGBM, Random Forest, and Decision Tree classifier based on more than one million data entries reached accuracies of 98.5% to 99.3% in crop recommendation tasks based on soil nutrients and environmental data (Bouni et al., 2024).

The application of ML in nutrient management in livestock production systems is still at an early stage but progressing fast. Various predictive models that can help in estimating manure nutrient content according to the diet, livestock species, body weight, and housing type have been developed to facilitate the implementation of precise manure management programs. The use of digital platforms that employ artificial intelligence models alongside satellite imagery has been employed in estimating biomass availability within integrated grazing systems in order to help in making decisions on the number of animals to graze in relation to the need to conserve nutrients in the soil (Oyedun et al., 2025).

4.3 Advantages of Data-Driven Decision Making

Decision-making through machine learning in ICLS nutrient management has numerous structural benefits compared to traditional methods. To begin with, machine learning algorithms can combine different types of information such as soil sensors, crop sensors, weather station data, satellite imagery, and animal production information into one predictive model to recognize complicated relationships between multiple variables which cannot be captured by traditional methods. Moreover, machine learning algorithms are self-adaptive because they can be trained or updated with new data as it comes in, becoming more accurate and relevant to the evolving situation, including climatic variability and new technologies employed in the management process. Lastly, decision-making tools based on machine learning algorithms can make predictions and suggestions at a resolution that is not possible for human decision-making systems.

One of the most crucial benefits of using ML algorithms in ICLS is the ability to estimate uncertainty in predictions, which is an essential requirement for risk-averse agricultural decisions. The use of ensemble methods such as random forests can provide prediction intervals, which would help make probabilistic recommendations for nutrient management.

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In other words, farmers could incorporate the inherent uncertainty of soil and weather characteristics when making their decisions (Folorunso et al., 2025).

The scalable nature of ML-based nutrient management solutions is yet another benefit. After training an ML algorithm on sufficiently diverse data samples, one can apply it at a relatively low cost to provide individualized nutrient management suggestions to numerous farmers simultaneously using a mobile app or online platform. Such solutions can become especially relevant when solving nutrient management problems in developing countries, where there is little capacity among extension services to reach out to all smallholder farmers.

5. METHODOLOGY: CONCEPTUAL FRAMEWORK

5.1 Study Design (Conceptual Approach)

As stated above, the methodology described in the current chapter is conceptual in nature and intended as a blueprint for empirical application by agricultural field researchers attempting to establish data-driven nutrient management within the ICLS. It involves the delineation of three main phases: (1) data gathering and synthesis throughout all the various components of the ICLS; (2) ML modeling and validation for nutrient prediction and flow optimization; and (3) implementation of a DSS to inform recommendations for nutrient management. Such a methodology is based on considerations of the limitations inherent in conducting agricultural research.

The conceptual design of the study is based on systems thinking, according to which the ICLS is viewed as a coupled human–environment system, through which nutrients move between different components: soil, plants, animals, and air. This differs greatly from the conventional approach whereby each of the abovementioned components is optimized individually, disregarding any connections and dependencies between these elements. As such, the data collection framework should account for the boundaries of the entire system.

5.2 Key Variables and Data Structure

The data structure that underlies the ML models includes four types of variables: (1) soil variables, namely total nitrogen (N), available phosphorus (P) and potassium (K), soil organic carbon (SOC), soil pH, bulk density, soil electrical conductivity, and microbial biomass carbon; (2) crop variables, such as above-ground biomass, leaf area index (LAI), plant chlorophyll content, vegetation indexes from remote sensing (NDVI, SAVI, EVI), and crop grain/forage yield; (3) livestock variables, like live weight, daily feed intake, manure volume and composition, milk/meat production, and grazing intensity; and (4) environmental variables, for instance daily maximum and minimum temperatures, precipitation, solar radiation, and relative humidity.

Data from all these four dimensions are obtained at different spatial resolutions—field scale, paddock scale, and landscape scale—and various temporal resolutions. Data collection for soils is seasonal or annual, using either grid sampling or stratified random sampling approaches. Crop data collection happens weekly to bi-weekly during the growth period, using in-situ sensors and unmanned aerial vehicle (UAV) imagery. Livestock data collection occurs daily through animal tracking and management information systems. Environmental data collection is done in real-time using on-farm weather stations complemented by high-resolution gridded reanalysis datasets.

5.3 Proposed Machine Learning Models

Proposed models for the three tasks in the ICLS nutrient optimization scheme include three categories of ML models for each different task. The first set of models includes those predicting the distribution of nutrients such as N, P, K, and SOC within the ICLS farm based on sensors, remote sensing images, terrain attributes, and history of farm management practices. Algorithms like random forests and XGBoost are suggested for use in these models since they are resilient to noise in data, can capture non-linear relationships, and their variable importance measures make them interpretable. Research studies have shown that these two algorithms yield R^2 scores of 0.75-0.90 for soil nutrient predictions (Folorunso et al., 2025).

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The second group comprises models of nutrient dynamics that describe how soil nutrient availability changes over time in response to weather conditions, plant growth, and manure applications. LSTM neural networks are suggested for use in predicting time series because of their known capabilities in modeling sequential dependence in agricultural data. The third class includes optimization models that use the output from the two previous types of models to determine the optimum time, quantity, and location of manure and fertilizer applications so as to reduce nutrient loss and fulfill the nutrient requirement of crops during the growing period. RL algorithms are recommended for use as an optimizer in the last layer of the architecture since they can learn optimal policies based on interactions within the simulated environment.

5.4 Workflow for Nutrient Flow Optimization

The ML-based nutrient optimization procedure works according to a process consisting of four stages in sequence. In the first stage, data ingestion, both current and past data collected from sensors installed in the soil, remote sensing platforms used to monitor crops, weather stations, and animal production facilities are consolidated into a cloud-based data repository. In the second stage, feature extraction, features such as heat units accumulated, soil moisture deficits, days after manure application, and spectral ratios of reflectance are extracted from the raw data stream. In the third stage, model inference, machine learning models make predictions of the current status of nutrients in soil, nutrient requirements of crops, and nutrient losses that may occur under certain farm management options. In the fourth stage, decision generation, the optimization tool converts predictions into decision support information for manure application and other related tasks.

The feedback loop is embedded within the process flow so that there is continual improvement in the model: The decision made by the managers on the ground produces data (the actual amount of nutrients absorbed, the yield, the soil test results) which will be used to further refine the datasets and train the models on an annual basis. This learning structure is critical to ensure that the models stay current as the farm environment changes.

6. PROPOSED FRAMEWORK FOR NUTRIENT FLOW OPTIMIZATION

6.1 Input–Output Structure of the System

The optimization of nutrient flow framework treats the ICLS as a system with specific input factors, flow through the system, and output factors. The main inputs are synthetic fertilizers, nitrogen deposition, nitrogen fixation by leguminous cover crops/pasture species, and feed inputs from sources external to the farm boundary. The main flows in the system include production and utilization of manure, recycling of plant residues, depositing of root exudates, and nutrient transformations in the soil-plant-animal systems. The outputs in the system are grain and forage removal, livestock products removal (meat, milk), loss of gases like nitrous oxide (N₂O), ammonia (NH₃), nitrogen gas (N₂), and nutrient leaching.

The objective function of the optimization problem can be stated as the maximization of nutrient retention in the system, that is, the proportion of nutrients retained in the harvestable output compared to the total input of nutrients, under conditions of restrictions based on crop nutrient requirement, soil nutrient accumulation, and environmental loss levels. The productivity objective of supplying enough nutrients for efficient crop and livestock production is complemented by the sustainability objective of minimizing environmental nutrient release. The machine learning framework possesses the prediction power needed to assess the state variables of the system, such as soil nutrient levels, crop nutrient requirements, and expected nutrient losses.

6.2 Integration of Crop and Livestock Components

An important element of the proposed DSS solution is the integrated approach to addressing crop and livestock enterprises with respect to nutrient management in a single nutrient balancing and optimization model. Unlike approaches that solve two separate nutrient balancing issues using two independent advisory systems, the DSS proposed keeps the unified nutrient balance sheet taking account of the N, P, and K flows into and out of all compartments simultaneously.

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It allows for joint optimization of crop and livestock management, for instance, optimizing the timing of manure spreading for matching nitrogen demand in crops, as well as livestock stocking to match forage supply while reaching targeted soil nutrient status levels.

Such an integration is implemented by a shared data layer connecting animal husbandry records with soil and crop monitoring data on a spatial level. Spatial distributions of animals in grazed fields can be estimated with the help of GPS tracking or field logs and serve as the starting point of soil nutrient balance models in the following crop growing seasons. The information about the nutritional content of feed provided to animals within livestock enterprises can be used as input into stoichiometric manure composition models calibrated on empirical manure analysis data.

7.3 Decision Support Mechanism

The decision support mechanism converts predictions from the ML algorithms into actionable guidelines for farm managers using a user-friendly computer interface. This interface presents the information on spatial soil nutrient levels using spatial maps, projections of crops' nutrient requirements and soil's nutrient provision capabilities during the upcoming growing period, recommendations for manure application rates and timing per management zones, additional fertilizers needed for nutrients not provided by manure application, and alerts for instances where nutrient losses exceed the specified environmental thresholds. Information about uncertainty of predictions will be conveyed using probabilities and different scenarios can be compared with the use of a scenario comparison module.

Context sensitivity is another key feature of our DSS design. After calibration of the models with farm-specific data from one or two seasons, the ML algorithms will become customized based on the specifics of farm management including its soil types, crops planted, type of livestock raised, and management procedures. Before being calibrated with the farm-specific data, regional data such as soil characteristics from surveys, climate data, and agronomic studies will be used to initialize the models to provide reasonable initial recommendations.

7. DISCUSSION

The theory proposed in this chapter will aid in developing the emerging research area of data-driven Integrated Crop–Livestock Farming nutrient management by providing a comprehensive, systems-based perspective towards optimizing nutrient flows that takes into account all facets of the crop–livestock relationship. A number of important points can be drawn from the synthesis of nutrient cycling knowledge and ML technique.

Most importantly, ML's potential for aiding Integrated Crop–Livestock Farming nutrient management recline on an adequate data foundation. ML algorithms trained using incomplete and biased datasets will result in recommendations that neglect important nutrient processes, most critically those occurring in the soil microbiome, which mineralizes organic materials and regulates the nitrogen cycle, and those relating to manure deposition patterns due to grazing. Investments in effective data acquisition technologies such as IoT-enabled soil sensors, UAV crop imaging, and animal tracking technology must therefore precede any practical application of ML in Integrated Crop–Livestock Farming nutrient management.

First, the development of an analytics platform that leverages AI techniques is relatively easier than the other two components discussed above. The development of such a platform would entail combining data from crop and livestock production operations and then applying AI techniques such as machine learning algorithms to analyze this data. Second, the integration of information on crop production and livestock production in one analytics platform is the most powerful as well as the most challenging component of this technology solution. At the moment, there exist agricultural data management platforms that operate separately in regard to crop, livestock, and soils.

Third, using ML-based decision support systems by farmers would call for considering some human elements in the adoption of technology that have often been underestimated by studies dealing with the adoption of technology innovations. In this context, farmers are likely to use the tool provided they feel confident that their decisions emanate from transparent algorithms with credible past performance and compatibility with local knowledge.

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Although the adoption of explainable algorithms and user-friendly DSS interfaces would address this issue, more needs to be done for its success.

Lastly, the environmental performance of ML-optimized nutrient management for ICLS should not only be assessed based on the performance of nutrient management at the farm scale, but also taking into account the total lifecycle impacts of nutrients, as well as potential negative externalities like the carbon footprint of the data collection process and associated technologies (sensor manufacturing, electricity usage), and even the phenomenon whereby improved efficiency results in increased production. Incorporation of the concepts of life cycle analysis into the nutrient flow optimization framework would thus offer a more holistic perspective on the environmental impact of data-driven nutrient management for ICLS.

One important drawback of the current framework is the presupposition that the required data collection capacity and technical expertise are already in place to build effective ML-based decision-making systems. In the context of smallholder farms in South Asia and sub-Saharan Africa, this may not always be the case, making simpler, data-lighter methods – such as rule-based decision trees based on expert knowledge – more suitable as a starting point. The ML approach must thus be seen as an aspirational future model that can be gradually built up towards from simple data collection and modeling processes onwards.

CONCLUSION AND FUTURE PERSPECTIVES

A conceptual framework to optimize the nutrient flow within Integrated Crop–Livestock Farming through data-driven solutions has been presented in this chapter. Leveraging insights from the theory of Integrated Crop–Livestock Farming nutrient cycles, the weaknesses associated with traditional nutrient management practices, and advances made in the field of ML for agricultural applications, the framework tackles the key problem of managing the intricacies and complexities involved in optimizing nutrient cycles within Integrated Crop–Livestock Farming.

In this regard, the main contributions made by this chapter include two aspects. Firstly, the chapter offers a concise summary of the nutrient cycling theory in relation to Integrated Crop–Livestock Farming that helps identify essential variables and parameters that should be considered when designing

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ML models for nutrient cycle optimization. Secondly, the chapter puts forth a framework to develop ML algorithms that can help manage the soil information, predict crop nutrient requirements, and optimize manure application processes.

A number of priority areas of future research arise from the foregoing discussion. One is the need for validation experiments to measure the real-world efficacy of ML-enabled nutrient optimization systems in various Integrated Crop–Livestock Farming environments characterized by different crop–animal interactions, soils, and climatic regions. The experimental design must be sound enough to allow comparisons with traditional farming practices as well as identify sources of improvement due to each individual component of the ML system. Secondly, the establishment of freely accessible, standardized data formats for Integrated Crop–Livestock Farming monitoring will greatly enhance the availability of training data sets for ML modeling.

Fourth, research into the governance issues around such use of AI for decision making about agriculture must include examination of questions surrounding data ownership, algorithmic accountability, and equity of benefit between different stakeholders, such as farmers, technology companies, and rural populations. Finally, incorporating precision nutrient management based on machine learning with existing carbon credit models would allow farmers to measure and possibly earn economic benefits from carbon savings due to precision nutrient management.

In summary, the merging of Integrated Crop–Livestock Farming systems and machine learning approaches is one area where innovation promises new opportunities for sustainable intensification of agriculture. By conceptualizing nutrient flow optimization problems as a data science problem within the context of Integrated Crop–Livestock Farming ecology and agronomy, there is an opportunity to increase farm productivity, minimize environmental nutrient leakage, and create resilient agricultural systems in the face of a changing climate. Achieving this goal will necessitate ongoing research cooperation among soil scientists, agronomists, animal scientists, data scientists, and rural development professionals.

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CHAPTER 3
**OPERATIONAL MODELS AND POLICY
FRAMEWORKS FOR FOOD BANKS IN CENTRAL
AND EASTERN EUROPE: INSIGHTS FROM A
ROMANIAN CASE STUDY**

¹Andrei BORȘA

¹University of Agricultural Sciences and Veterinary Medicine Cluj-Napoca, Cluj-Napoca, Romania, andrei.borsa@usamvcluj.ro, ORCID ID: 0000-0001-7887-8639

INTRODUCTION

Context: Food Waste, Food Insecurity and the Rise of Food Banks in Europe

Food waste represents one of the most pressing paradoxes of contemporary agri-food systems: approximately 40% of all food produced for human consumption is lost or wasted globally, generating between 8% and 10% of total greenhouse gas emissions and consuming an agricultural land area larger than China and India combined (FAO, 2022; GFN, 2022). Within the European Union, the scale of this challenge is equally alarming: in 2023, the EU generated approximately 58.2 million tonnes of food waste — roughly 130 kilograms per inhabitant and an estimated €132 billion annually — with households responsible for more than half of this total (53%), followed by manufacturing (19%), restaurants and food services (11%), primary production (10%) and retail (8%) (Eurostat, 2025; European Commission, 2025).

This systemic inefficiency unfolds against a backdrop of persistent food insecurity: in 2023, 9.5% of the EU population — nearly 42 million people — were unable to afford a quality meal every second day, with particularly alarming rates among those at risk of poverty in CEE countries such as Slovakia (45.7%), Hungary (44.9%) and Bulgaria (40.2%) (Eurostat, 2024). In response to this dual crisis of abundance and deprivation, food banks have emerged as critical social infrastructure across Europe. Founded in 1986, the European Food Banks Federation (FEBA) coordinates 351 food banks across 30 European countries; in 2024 alone, FEBA members redistributed approximately 834,000 tonnes of food, serving about 12.2 million beneficiaries through 43,345 charitable partner organisations, sustained by over 100,686 volunteers (FEBA, 2024).

At the global level, the Global FoodBanking Network (GFN) reported that, in 2024, food banking organisations provided assistance to over 38 million people across 46 countries, with food distribution increasing by 50% since 2018 (GFN, 2024). In early 2026, the European Parliament explicitly recognised the essential role of food banks in combating poverty and affirmed access to food as a fundamental human right, marking a shift from purely charitable models towards rights-based food governance frameworks (FBAR, 2026).

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Despite this growth, significant geographical asymmetries persist: food banks in Central and Eastern Europe remain comparatively underdeveloped and understudied, having emerged later and with limited infrastructure relative to their Western European counterparts (Greiss et al., 2023). Romania illustrates this paradox acutely: with over 3.45 million tonnes of food wasted in 2022 and approximately 28% of its population at risk of poverty, the country simultaneously leads European food waste rankings and confronts one of the bloc's highest rates of food insecurity (FBAR, 2026).

Problem Statement and Research Objectives

Although the literature on food bank operations and food waste governance has expanded considerably over the past decade, significant knowledge gaps remain, particularly with regard to CEE contexts. Existing operational research models for food banks — primarily developed for North American and Western European settings — tend to simplify or omit variables critical in CEE environments, such as volatile donation flows, limited cold-chain infrastructure, high volunteer dependency, and fragmented multi-stakeholder coordination (Fikar et al., 2023; Van Donselaar et al., 2023). Similarly, comparative policy analyses of food waste reduction strategies rarely include CEE countries as distinct governance units, leaving a gap in our understanding of how institutional context shapes the effectiveness of food bank-based redistribution models (Östergren et al., 2014; European Commission, 2023)

This chapter addresses these gaps by pursuing three interconnected objectives: (1) to map and critically examine existing operational models for food banks, with attention to the specific logistical, infrastructural, and governance challenges characterising CEE agri-food systems; (2) to analyse the public policy frameworks governing food donation and redistribution in CEE countries, identifying key legislative gaps, barriers, and opportunities for reform; and (3) to present an in-depth Romanian case study, grounded in practitioner experience and operational data, that illustrates how a food bank can function as both a logistical mechanism and a social innovation actor within a transition economy.

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Structure of the Chapter

The remainder of this chapter is organised as follows. Section 2 establishes the theoretical background, reviewing the literature on food banks in agri-food governance, social innovation, and circular economy frameworks. Section 3 examines and typologises operational models of food banks, with particular focus on supply chain processes and logistics. Section 4 analyses the public policy landscape for food banks in CEE, identifying key gaps and inconsistencies relative to EU-level frameworks. Section 5 contextualises the Romanian agri-food system in terms of food insecurity, food waste generation, and the historical development of food banking. Section 6 presents the Romanian case study, drawing on primary operational data and practitioner insights to illustrate both achievements and structural limitations of the current model. Section 7 integrates these findings in a discussion of the links between operational models, policy frameworks, and the potential of food banks as drivers of circular agri-food systems. The chapter concludes with evidence-based recommendations for policy and future research directions.

1. THEORETICAL FRAMEWORK

1.1. Food Banks as Eco-Social Actors: Doughnut Economy and Eco-Social Research

Understanding food banks as social organisations requires a theoretical lens that holds together the imperatives of social justice and ecological sustainability. Eco-social research — an emerging interdisciplinary field that synthesises ecological systems thinking with social welfare theory — offers a particularly productive framework (Dominelli, 2012). It argues that social problems such as poverty and food insecurity cannot be addressed in isolation from the environmental systems that sustain human life, and that welfare institutions must be evaluated according to both their social effectiveness and ecological embeddedness (Rittel, 2023).

A central reference is Kate Raworth's (2017) Doughnut Economy model, which conceptualises sustainable development as the space between a social foundation — comprising dimensions of well-being such as food, water, health, housing and political voice — and an ecological ceiling defined by planetary boundaries including climate stability, biodiversity and freshwater cycles.

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Applied to food systems, the Doughnut framework requires food governance actors to prevent people from falling below the social foundation (food insecurity, malnutrition) while preventing collective resource use from breaching planetary boundaries (greenhouse gas emissions, land degradation, food waste). Food banks, positioned at the intersection of food surplus and food need, are thus structurally relevant to both dimensions.

However, critical scholarship questions whether food banking organisations, in their current form, genuinely correspond to an eco-social understanding of sustainability. Rittel (2023), in a thematic content analysis of FEBA and the German national food bank network (TAFEL), finds that the dominant organisational approach is marked by high systemic embeddedness — operating within and reinforcing the existing economic logic of food surplus rather than challenging the structural conditions that produce it. This critique implies that food banks, as currently designed, have limited transformative potential and risk becoming a permanent institutional patch for a dysfunctional food system. For food banks in emerging EU economies, where welfare state alternatives are even more constrained, this tension underscores the need for models that embed ecological and social transformation as explicit organisational goals.

1.2. Circular Economy in Food Systems: Valorisation of Surplus and Urban Food Infrastructures

The circular economy (CE) provides a complementary theoretical lens for reframing how food banks relate to resource flows in agri-food systems. Drawing on foundational CE principles articulated by the Ellen MacArthur Foundation (2013) — eliminate waste and pollution by design, keep materials in use, and regenerate natural systems — circular food systems aim to close nutrient and resource loops across the entire food supply chain, from primary production to post-consumption valorisation. In a circular food system, edible surplus is redistributed before it becomes waste, inedible by-products are valorised as inputs for new processes (feed, biogas, compost, ingredients), and cities function as circular metabolisms that capture and recirculate biological and technical materials.

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Urban infrastructures play a decisive enabling role in this transition. As the Ellen MacArthur Foundation (2022) notes, cities — which will consume 80% of all food by 2050 — are uniquely positioned to catalyse the circular shift through infrastructure investment, public procurement, and digital tools that connect surplus to scarcity at the local level. Within the EU Circular Economy Action Plan, circular food system indicators explicitly include the valorisation of food by-products, redistribution of surplus, and selective collection for high-level biological recovery, providing a policy anchor for positioning food banks as active circular infrastructure rather than as passive receivers of unwanted goods. The systematic integration of circular economy practices throughout the food bank supply chain remains incomplete, particularly in low-resource contexts where infrastructure gaps, regulatory barriers, and financing constraints limit the scope for valorisation.

1.3. Social Innovation and Social Enterprise in Food Systems

A third theoretical pillar is provided by the literature on social innovation and social enterprise in food systems. Social innovation is broadly defined as the development of new ideas, services, models, and collaborations that meet social needs while creating new social relationships (European Commission, 2013; Mulgan, 2007). In the food domain, it covers initiatives ranging from community supported agriculture and solidarity stores to food rescue hubs, participatory supermarkets, and digital food-sharing platforms, all aiming to reconfigure food system relations to improve equity, sustainability, and resilience.

A systematic review by Wan et al. (2023) shows that social innovation is widely deployed in food waste reduction across Europe and beyond, but highlights gaps regarding performance indicators, governance of social supermarkets, and the complex relational networks of food rescue initiatives. Social enterprises, defined as hybrid organisations that combine a social mission with revenue generation and participatory governance (Defourny & Nyssens, 2017), are seen as particularly effective vehicles for alternative food systems.

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For food banks, moving from a purely charitable model towards a social enterprise logic implies shifting from dependency on donated surplus to more proactive sourcing, from volunteer-based operations to professionalised logistics, and from redistribution as an end in itself to broader social and ecological transformation.

2. FROM CHARITY MODEL TO HYBRID CIRCULAR MODELS

2.1. The Charity Food Bank Model: Characteristics and Critiques

The dominant institutional form of food banking globally is the charity model, a supply-driven and reactive logic based on collecting and redistributing donated or unsold surplus from retailers, manufacturers, and producers to people in need via partner charities. In this configuration, food banks act mainly as logistical intermediaries – sorting, storing, and distributing products that would otherwise be wasted – without directly engaging in production or pricing and without generating independent revenue from redistribution (Riches, 2018; Caraher & Furey, 2018).

From a food justice and rights-based perspective, the model is criticised for its structural dependence on corporate surplus, which means that volume, quality, and nutritional profile are determined by commercial overproduction and retail logistics rather than by assessed need, creating unstable and often nutritionally imbalanced supply (Riches, 2018; Caraher & Furey, 2018).

This institutionalisation of charitable food risks normalising food insecurity as a matter for philanthropy rather than structural reform, while reliance on volunteers and corporate partnerships limits investments in professionalisation and advocacy. Eco-social critiques emphasise that the charity model exhibits high systemic embeddedness, operating within and reinforcing the productive logic that generates both surplus and deprivation instead of challenging it (Rittel, 2023). Ethnographic research also documents experiences of shame, stigma, and loss of autonomy among recipients of pre-selected parcels, underscoring the need to explore hybrid and circular alternatives that can address logistical, social, and ecological shortcomings simultaneously (Stuit et al., 2025).

2.2. Hybrid Models: From Redistribution to Transformation ***Food Bank–Social Supermarket Model***

The social supermarket — a not-for-profit social enterprise that sells food at symbolic or heavily discounted prices to low-income individuals, typically sourced from surplus food streams — is one of the most significant innovations in food aid provision over the past decade. Social supermarkets emerged in CEE contexts following the 2008–2014 economic crisis, with approximately 380 organisations active across the EU by the early 2020s (Mihai, 2021). Research in Croatia, Lithuania, Poland and Serbia indicates that they are perceived as dual-purpose instruments — reducing food waste while providing dignified food access — although their effectiveness depends strongly on legal frameworks, welfare system integration and state support (Szmyt et al., 2021). Studies by the University of Birmingham show that social supermarkets function as transitional spaces that mitigate the social segregation associated with conventional food banks, providing choice, dignity and community belonging (Moraes et al., 2024).

Food Bank with By-Product Recovery and Minimal Processing

A second hybrid model integrates food banks into circular valorisation chains by expanding their scope beyond the collection of retail surplus to include the recovery of agricultural by-products, near-expiry raw materials and food processing residues that can be minimally transformed into edible products. In this configuration, food banks act as processors as well as redistributors, preparing soups, dried or preserved products or ingredient kits from unsaleable primary produce, thereby increasing the volume and quality of food available while generating employment and knowledge assets. FEBA’s 2025 workshop on Food Surplus Management in Tirana articulated this vision of food banks as urban food surplus hubs that unlock social, economic and ecological value by connecting cities, food banks and local stakeholders (FEBA, 2025). This model aligns directly with circular economy principles of keeping materials in use at the highest possible value cycle.

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Food Bank–Digital Platform Model

A third hybrid model leverages digital technology to transform food bank operations from centralised, warehouse-dependent systems into networked, real-time redistribution platforms. The most documented example is FoodCloud (Ireland), a tech-based social enterprise that developed the Foodiverse application, enabling direct peer-to-peer redistribution between retail and food service surplus generators and local community organisations. As of 2024, Foodiverse redistributes over one million meals weekly across Ireland, the UK, the Czech Republic, Slovakia, Kenya and Indonesia, with around 30% of all food in Ireland now redistributed through virtual models compared to a global average of only 5% (FoodCloud, 2024). The European Commission identifies online platforms as strategic tools for scaling food surplus redistribution by integrating demand–supply matching, digital traceability and analytics into food bank operations; these virtual models reduce warehousing needs, lower transportation costs and generate granular data on surplus volumes, flows and beneficiary needs.

2.3. A Proposed Continuum: From Charity to Circular Social Enterprise

Drawing on the above analysis, this section proposes a conceptual continuum articulating the progression from the classic charity food bank model towards a fully integrated circular social enterprise. The continuum is defined across four dimensions: governance structure, revenue streams, role in circularity, and degree of beneficiary empowerment. Table 1 synthesises these dimensions across three ideal-type positions on the continuum.

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Table 1. Conceptual continuum from charity food bank to circular social enterprise: CHARITY FOOD BANK → HYBRID MODEL → CIRCULAR SOCIAL ENTERPRISE

Dimension	Charity Food Bank	Hybrid Model	Circular Social Enterprise
Governance	Hierarchical NGO; donor-driven	Mixed NGO and social enterprise logic	Participatory, multi-stakeholder, rights-based
Revenue streams	Donations and grants	Donations, symbolic sales, service fees	Diversified sales, services, processing, grants, public contracts
Role in circularity	Passive receiver of surplus	Active redistribution with partial valorisation	Full integration of sourcing, valorisation, processing, and nutrient loop closure
Beneficiary empowerment	Low: pre-selected parcels, stigma	Medium: choice, dignity, transitional support	High: co-design, participation, food literacy, advocacy

Source: author's conceptualisation based on the analytical framework developed in the chapter.

At the left pole of the continuum, the classic charity food bank operates as a reactive logistical actor with no revenue generation and limited transformative aspiration. At the right pole, the circular social enterprise is a proactive agri-food system actor that integrates multiple circular functions, diversifies revenue, and embeds beneficiary participation in governance and service design. Hybrid models occupy an intermediate position, combining elements of both. For food banks in emerging EU economies such as Romania — characterised by infrastructure constraints, regulatory gaps, and high rates of food insecurity — the hybrid model represents the most immediately achievable step in this transition, with the circular social enterprise as a strategic horizon.

3. POLICY FRAMEWORKS FOR FOOD BANKS IN CENTRAL AND EASTERN EUROPE

3.1. International and EU-Level Policy Context

Food banks operate within a multi-layered governance architecture spanning international, European, and national policy frameworks. At the international level, the most overarching mandate is provided by the United Nations Sustainable Development Goal (SDG) Target 12.3, which commits signatory states to halving per capita food waste at the retail and consumer level and reducing food losses along production and supply chains by 2030 (FAO, 2022; European Commission, 2024). The Global FoodBanking Network, active in nearly 50 countries, has invested over USD 48.7 million in grants and supported 580 food banking professionals globally since 2006, while explicitly advocating for national food donation policies as an essential lever for accelerating progress towards SDG 12.3.

At the European level, the regulatory and strategic landscape for food waste reduction and food donation has been significantly reshaped by the European Green Deal and its flagship instrument, the Farm to Fork (F2F) Strategy, adopted in 2020. The F2F Strategy commits the EU to halving per capita food waste at retail and consumer levels by 2030 and to developing legally binding food waste reduction targets for Member States. In 2017, the European Commission adopted EU Food Donation Guidelines — updated through Commission Regulation (EU) 2021/382 — to facilitate compliance of donors and recipients with relevant EU regulatory requirements, covering food safety, food hygiene, traceability, liability, and VAT (European Commission, 2017). However, these guidelines remain non-binding orientations rather than harmonised directives, leaving significant implementation discretion to Member States and creating heterogeneous national regulatory environments. The European Food Banks Federation (FEBA) has played a pivotal advocacy role, including co-developing the Global Food Donation Policy Atlas — a comparative legal framework evaluating national food donation laws in 27+ countries — as a tool for identifying best practices and advocating for policy harmonisation.

3.2. National Food Donation and Waste Reduction Policies in CEE

Despite the existence of an enabling EU framework, national implementation across CEE countries remains uneven, marked by legislative fragmentation, inconsistent fiscal treatment of donations, and the lack of integrated strategies that connect food waste reduction with investment in food bank infrastructure. A study for the European Economic and Social Committee showed that, while some Western countries such as France and Spain introduced tax credits for food donations, several CEE states continued to levy VAT on donated products, effectively penalising donation compared to disposal (Deloitte, 2014).

Romania illustrates how policy ambition can outpace implementation capacity: Law 217/2016 on Food Waste Reduction created a hierarchy of measures prioritising prevention, discount sales, and donation, but entered into force without the necessary implementing regulations and remained inapplicable for almost three years. These norms were eventually adopted in January 2019, and were further substantially amended by Law 49/2024, which introduced mandatory anti-waste plans, legal obligations to donate unsold products, tax incentives linked to the Fiscal Code (Law 227/2015), and sanctions of between 2,000 and 4,000 euro for non-compliance (Romanian Parliament, 2024). From 2026, agri-food operators are required to report annually the quantities donated or wasted, marking a meaningful step towards accountability.

3.3. Gaps and Inconsistencies in Public Policy

The 2023 European Commission assessment on barriers and opportunities in food surplus redistribution — drawing on responses from 18 Member States, 19 stakeholder groups, and 14 FEBA members — identified a consistent set of structural barriers particularly acute in CEE settings:

- the absence of coordinated national strategies explicitly integrating food banks into food waste governance frameworks;
- sparse knowledge of volumes saved through donation at the national level;

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- significant ambiguity regarding the roles of relevant ministries at national, regional, and local levels (European Commission, 2023).

Legislative clarity represents the first major gap. The sequential adoption of Law 217/2016 without operational norms, followed by years of amendment, created regulatory uncertainty that deterred potential food donors and complicated food bank operational planning. Similar patterns of legislation without adequate implementation infrastructure have been observed across other CEE contexts, where multi-ministerial responsibility generates overlapping competences and slow inter-institutional coordination. Where tax incentives for food donation are absent or unknown, food businesses frequently find it economically rational to destroy or discard surplus rather than donate it — particularly when donation involves logistics costs not offset by any fiscal benefit (Szymańska-Brałkowska, 2022). A third, structurally significant gap concerns the absence of dedicated public co-financing schemes for food bank infrastructure in CEE, constraining the expansion of cold-chain and logistics capacities necessary for scaling redistribution operations.

4. ROMANIAN CONTEXT: FOOD INSECURITY, FOOD WASTE AND THE EMERGENCE OF FOOD BANKS

4.1. Socio-Economic Profile and Food Insecurity in Romania

Romania presents one of the most acute food insecurity profiles in the European Union, characterised by deep structural vulnerabilities that cut across income, geography, and social class. According to Eurostat (2024), approximately 28% of Romania's population faces the risk of poverty — a figure consistently above the EU average of 16.2% — while food insecurity at the household level is compounded by pronounced urban–rural asymmetries. Over 60% of rural families are classified as poor, and rural areas concentrate disproportionate shares of vulnerable populations: elderly households, large families with children, and agricultural workers with irregular or subsistence incomes (FBAR, 2026). A dedicated survey of 875 rural consumers found that food insecurity is primarily driven by constraints in food availability and access, with structural factors such as distance from retail outlets, limited transport infrastructure, and low monetary income creating persistent barriers to adequate nutrition (Muntean et al., 2024).

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At the national level, food insecurity manifests differentially across population segments. An estimated 46% of Romanian children under six years of age living in rural areas face the risk of poverty and malnutrition (FBAR, 2026). In urban areas, food insecurity is concentrated among single-parent households, long-term unemployed individuals, newly arrived migrants, and elderly people relying solely on minimum pensions. The NGO sector serves as the primary institutional vehicle for reaching these groups — a role that has expanded significantly since the early 2000's as state social services were progressively decentralised and underfunded. FBAR's nine regional food banks currently partner with over 930 charitable organisations that manage food assistance programmes across the country, representing one of the largest civil society networks in the Romanian agri-food sector.

4.2. Food Waste in Romanian Agri-Food Systems

Romania generates approximately 2.5 million tonnes of food waste annually — equivalent to 150 kilograms per person — placing the country among the highest in the EU in terms of per capita generation (Eurostat/FAO data cited in FBAR, 2026; Radio Romania International, 2025). This figure translates into over 6,000 tonnes of food discarded daily, representing an enormous pool of potentially redistributable food surplus that the existing food banking infrastructure is currently far from fully recovering. The distribution of food waste across supply chain segments reveals that the largest waste generators are restaurants and food service operators (approximately 8.6% of total), followed by urban consumers (6.5%), agricultural production (4.2%), food processing (3.8%), and retail (0.9%) (ANSVSA data cited in Spotmedia, 2025).

Notably, 95% of all food waste in Romania originates in urban areas, despite rural populations being disproportionately food-insecure — a structural paradox that underscores the need for effective redistribution mechanisms linking urban surplus to rural need. A 2025 study by Up Romania and Reveal Marketing Research found that 46% of Romanians discard cooked food, the primary causes being over-purchasing (43%) and products passing their best-before date (Up Romania & Reveal, 2025).

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The main donatable surplus streams within the Romanian agri-food system are: near-expiry retail products; agricultural culls and grading rejects; processing residues and overstocked ingredients; and prepared food from HoReCa operators, now subject to mandatory doggy-bag provisions under Law 49/2024. These flows collectively constitute a recoverable surplus that, if systematically channelled through food bank infrastructure, could contribute substantially to Romania's SDG 12.3 targets.

4.3. The Emergence and Development of Romanian Food Banks

The food banking movement in Romania emerged in the mid-2010s as a civil society initiative, modelled on FEBA principles and supported by international retail partners committed to integrating food waste reduction into their corporate sustainability strategies. The first Romanian food bank — Banca pentru Alimente București — was founded in July 2016, following an inaugural training visit to the Milan Food Bank (Banco Alimentare), and held its founding conference at the Romanian Chamber of Commerce and Industry in October 2016. From the outset, the organisational model was anchored in FEBA standards: a non-partisan, non-religious charitable association collecting surplus food from donor companies and redistributing it free of charge to NGO partners. The founding network of national partners included Lidl România, Metro Cash & Carry, Kaufland, Penny, Danone, Auchan, and Eti.

Scaling was rapid and driven by a combination of retail sector partnerships and targeted philanthropic funding. In 2017, the first year of operation, three banks collected 222 tonnes from 30 donor companies for over 22,000 people through 50 partner NGOs. By 2018, the regional network was extended to Cluj (July 2018) and Roman (December 2018). FBAR officially became an affiliate member of FEBA in 2018. By 2026, FBAR operates nine Regional Food Banks — in Bucharest, Cluj, Roman, Oradea, Braşov, Timișoara, Constanța, Craiova, and Galați (Fig.1) — having collectively redistributed over 39,000 tonnes of food products, equivalent to more than 76 million meals, to over 325,000 beneficiaries through approximately 930 partner organisations (FBAR, 2026).

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The Banca Regională pentru Alimente Cluj grew from 8.4 tonnes in 2018 (pilot year) and 65 tonnes in 2019 to over 1,900 tonnes in 2025 — an increase of over 2,800% in six years — covering the counties of Cluj, Alba, Bistrița-Năsăud, and Sibiu (Banca pentru Alimente Cluj, 2026).



Figure 1. Romanian Food Banks Federation (FBAR) network and territorial coverage of BRAC

Source: <https://www.bancapentrualimente.ro/retea/>

5. CASE STUDY: OPERATIONAL MODEL OF THE REGIONAL FOOD BANK CLUJ

5.1. Methodology and Data Sources

This chapter employs a qualitative case study methodology (Yin, 2018) centred on the Banca Regională pentru Alimente Cluj (Regional Food Bank Cluj — hereafter BRAC), one of the nine regional food banks constituting the FBAR network. The case study draws on a combination of insider/practitioner research and documentary analysis: the present author includes a founding member and operational manager of the BRAC, providing direct access to internal operational documents, logistics records, partner agreements, volunteer coordination data, and annual impact reports not publicly available in academic databases.

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This practitioner-research approach is epistemologically aligned with participatory action research (PAR) traditions in food system scholarship, which argue that the experiential knowledge of food system actors constitutes a primary and irreplaceable source of evidence for understanding the realities, constraints, and innovations of food banking organisations (Food Banks Canada, 2024; Thompson et al., 2018).

The justification for selecting BRAC as the case study unit is threefold. First, the organisation is empirically representative of the regional food bank model across the FBAR network and CEE food banking systems characterised by limited infrastructure, high volunteer dependency, and nascent digital capabilities. Second, BRAC has demonstrated a growth trajectory that captures, in compressed form, the institutional maturation and operational challenges characteristic of food banks in transition economies. Third, the organisation has been an early adopter of digital tools and ESG reporting practices within the FBAR network, making it an informative case for exploring the digitalisation and circular potential of Romanian food banking. Data presented in this section span the period 2019–2025 and are drawn from internal annual reports, operational logistics records, donor and partner databases, and the public-facing institutional communications of BRAC and FBAR.

5.2. Organisational Structure and Governance

BRAC operates as a non-profit association under Romanian civil law, affiliated with FBAR and, through FBAR, with the European Food Banks Federation (FEBA). The governance structure comprises a Board of Directors responsible for strategic direction, financial oversight, and partnership governance; an executive team of ten full-time or part-time staff managing day-to-day logistics, partner relations, and communications; and an extended volunteer community that constitutes the primary operational workforce for collection campaigns and sortation activities. The founding President, Gabriela Vereş, articulated the founding rationale as a direct progression from prior food waste education programmes: 'The Banca pentru Alimente project came as a natural result of school education projects initiated with the Food Waste Combat team. Sometimes it is not enough to educate people about waste — it is also necessary to do something concrete' (Banca pentru Alimente Cluj, 2026).

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The strategic partnership ecosystem of BRAC is multi-layered. At the donor tier, the organisation works with a network of retail chains — including Lidl, Kaufland, Penny, Metro, Auchan, and Cora — that provide near-expiry shelf products, produce, and non-food household items on a regular donation basis. Industrial donors and food processing companies contribute bulk quantities during seasonal surpluses or promotional overruns. Institutional partners — including Interreg Europe, the local municipality, and corporate sponsors through CSR programmes — provide financial and logistical support for operational scaling and national collection campaigns. At the beneficiary tier, 170 non-profit partner organisations active in 2025 — including social canteens, children's homes, day centres for the elderly, and refugee support organisations — receive food allocations according to assessed need and organisational capacity.

5.3. Logistics and Supply Chain Configuration

The logistics model of BRAC reflects the dual-channel supply chain architecture typical of European food banks operating under FEBA standards, combining both donor pick-up and warehouse receipt modalities (Fig. 2). Under the pick-up modality — the primary channel for routine weekly collections — BRAC vehicles collect donated products directly from retail partners and industrial donors according to fixed schedules, with frequency adjusted to donation volume, product perishability, and logistical efficiency. Under the warehouse receipt modality — dominant during national collection campaigns — volunteer teams stationed at retail partner stores collect food products donated by individual consumers and transfer them in batches to the central BRAC warehouse for sortation and redistribution.

The central warehouse — a single regional facility serving the counties of Cluj, Alba, Bistrița-Năsăud, and Sibiu — combines dry storage, refrigerated storage, and sortation areas. This infrastructure is managed by a core team of ten staff who, in 2025, managed over 1,500 tonnes of products through routine operations — a per-staff productivity ratio reflecting both operational efficiency and the systemic constraint imposed by a limited workforce.

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Fleet capacity encompasses refrigerated vehicles capable of transporting temperature-sensitive perishables — a cold-chain capability that distinguishes BRAC from smaller food distribution entities and enables compliance with food safety regulations. Peak-volume management during national campaigns relies predominantly on volunteer mobilisation: in winter 2025, when a vehicle arrival was blocked by snow, rapid mobilisation via the volunteer messaging group resulted in spontaneous attendance on three separate occasions to manually clear the platform and unload products — illustrating the substitution of social capital for formal logistics infrastructure (Banca pentru Alimente Cluj, 2026).

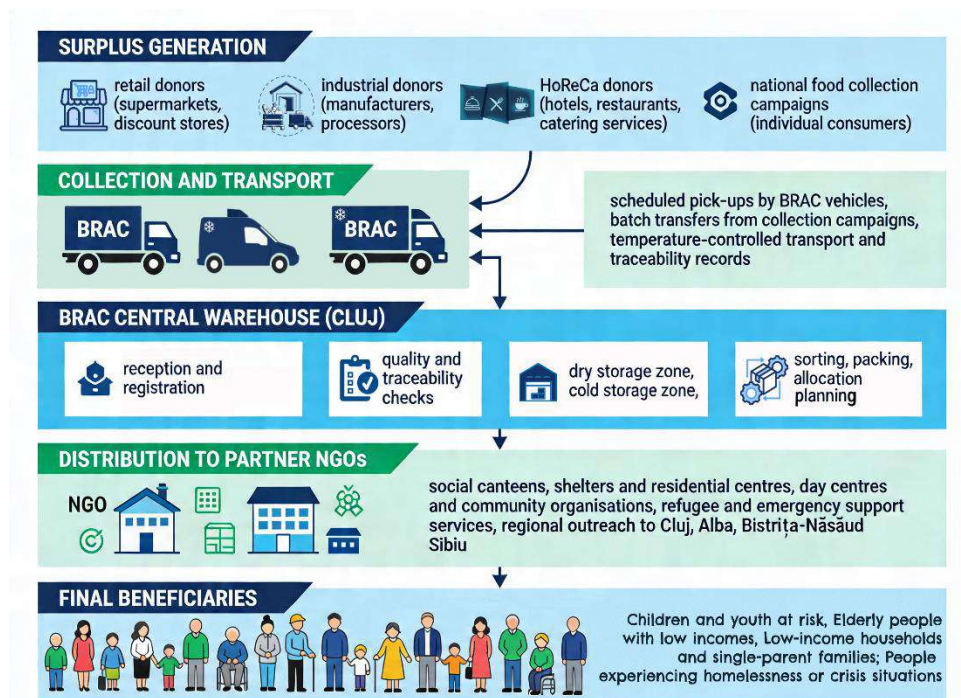


Figure 2. BRAC logistics and supply chain configuration

Source: author's conceptualisation based on the BRAC operational model described in the chapter.

5.4. Evolution of the food bank model in Cluj: challenges and lessons learned

Beginnings

The establishment of the Cluj Food Bank built explicitly on the Bucharest model and was accelerated by the presence of a small core team with complementary competencies in logistics, education, and legal/CSR frameworks. The author assumed responsibility for logistics design, reallocating staff and a vehicle from an existing company, and developing basic procedures for collection, transport, and food safety compliance. Parallel to this, the Food Waste Combat team and other awareness-raising partners contributed by identifying potential beneficiary NGOs and supporting the local embedding of partnerships with donors (Food Waste Combat, 2020). Legal and CSR specialists facilitated the negotiation of contracts with large retail chains and ensured a compliant framework for recurring donations, creating the institutional conditions for rapid local replication of the FEBA-type food bank model.

Challenges

Three clusters of challenges marked the early evolution of the model: food safety and liability, absence of standardised procedures, and low initial trust along the donation chain. Supermarkets operated in a highly regulated “white zone” with full HACCP documentation, while many NGOs functioned in a “grey zone” characterised by limited storage infrastructure, scarce resources, and informal practices, raising concerns about liability in case of foodborne incidents. At donor level, internal procedures for food donation were largely absent; surplus products were typically redirected to employees, sold at discount, or discarded as waste, and this disposal route was perceived as administratively simpler and less risky despite the associated costs. Both retailers and NGOs doubted that documentation, traceability, and responsibility would be consistently ensured from donor to final beneficiary, and NGOs in particular were accustomed to low levels of inspection and minimal formalisation.

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Solutions and development stages

The response strategy combined incremental risk management, gradual scaling of logistics, and progressive formalisation of relationships with partners. In the initial stage, operations focused on low-risk configurations: use of a refrigerated vehicle, prioritisation of beneficiaries with existing cooking and storage facilities, temperature monitoring along the entire flow, and basic staff training in hygiene, documentation, and traceability. Early agreements with retailers were implemented in a deliberately low-visibility mode, without media promotion, in order to test flows, monitor food safety outcomes, and build an evidence base (quantities, beneficiaries, absence of incidents) before public launch.

Once the model was validated operationally, the food bank transitioned to recurrent contracts and dedicated donation days, which transformed donations from ad-hoc events into predictable flows and enabled more professional planning on the NGO side. For large, atypical surpluses, joint planning mechanisms were introduced: donors announced volumes in advance, alternative valorisation options were explored, NGOs registered according to processing capacity, and distribution was organised accordingly. As funding became available, resources were directed towards expanding storage infrastructure and optimising logistics, including the introduction of co-payment mechanisms for transport and, later, the development of a dedicated warehouse located near motorway junctions to receive full truckloads under controlled conditions. Beneficiaries progressively shifted to a subscription-based model, paying a monthly fee and collecting allocations directly from the warehouse on predefined days, which improved cost recovery and operational predictability.

In parallel, the maturation of partnerships and integration into European networks such as FEBA generated demand for clearly defined performance indicators and transparent reporting, both for internal management and for corporate ESG disclosure. Under this evolving model, the Cluj Food Bank scaled into the Banca Regională pentru Alimente Cluj (BRAC), operating a single regional hub serving four counties and functioning as a reference regional food bank within the Romanian and CEE context.

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Key lessons learned

- Leveraging a pre-existing model (Bucharest Food Bank) and a compact team with complementary skills significantly reduces the duration and cost of the start-up phase.
- Perceived food safety and liability risks constitute a major barrier; discrete piloting with strict control and clear allocation of responsibility is crucial for building retailer confidence.
- Recurrent contracts and dedicated donation days convert food donation into a predictable resource stream that supports professional planning and stabilises NGO operations.
- Early investment in basic logistics (controlled-temperature vehicle, simple procedures, staff training), followed by shared infrastructure and cost-sharing mechanisms (warehouse, subscription model, transport co-payment), enhances both social impact and financial sustainability.
- Transparent reporting and robust KPIs are essential for accessing international networks such as FEBA and for enabling corporate partners to integrate food donation credibly into CSR and ESG strategies.

5.5. Outcomes and Performance Indicators

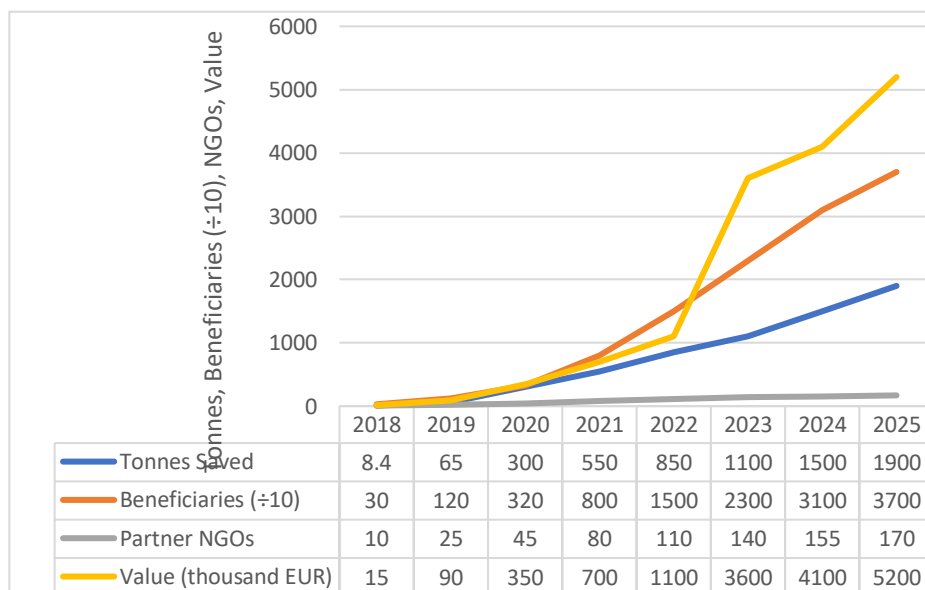
The operational performance of BRAC across 2019–2025 demonstrates a trajectory of consistent and accelerating growth exceptional within the CEE food banking context (table 2). In 2025, the 1,900 tonnes redistributed translate into over 3.8 million meal portions delivered to over 37,000 vulnerable individuals across four counties — at a commercial food value exceeding 5.2 million Euro — representing year-on-year growth of approximately 28% compared to 2024 and over 70% compared to 2023 (Banca pentru Alimente Cluj, 2026). Of this total, over 1,500 tonnes were collected through routine operational channels (excluding national campaigns), with a commercial value of over 4.42 million euro.

Applying the GFN (2022) carbon avoidance ratio of approximately 3.3 tonnes CO₂ equivalent per tonne of food redistributed, BRAC's 2025 performance implies an avoided emissions contribution of approximately 6,270 tonnes of CO₂ equivalent.

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At the institutional and community level, the growth in partner NGOs to 170 active organisations in 2025 — including 25 newly onboarded in that year — reflects the expanding territorial and social reach of BRAC's redistribution network. Partner testimonials identify three primary value dimensions: nutritional diversification of beneficiary diets; cost reduction for social organisations managing food preparation programmes (one partner, Asociația Masa Săracilor, reporting a 33% reduction in meal preparation costs); and the trust-based partnership model enabling continuous, non-crisis-contingent food access (Banca pentru Alimente Cluj, 2026).

Table 2. Key performance indicators of Banca Regională pentru Alimente Cluj (BRAC), 2018–2025



Source: Author's synthesis based on BRAC reports, 2018–2026.

6. DISCUSSION: LINKING OPERATIONAL MODELS AND POLICY FRAMEWORKS

6.1. How Policy Shapes Food Bank Operations in CEE

The empirical evidence from the BRAC case study demonstrates that the policy environment operates as an active determinant of operational scope,

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logistical efficiency, and institutional sustainability. Three policy-operation interactions are particularly salient. First, the protracted implementation gap of Law 217/2016 had direct consequences for BRAC's early-stage sourcing strategy: in the absence of clear liability protections and VAT treatment guidelines, several industrial donors declined to participate during 2018–2019, citing legal uncertainty and potential fiscal exposure. This regulatory vacuum effectively restricted BRAC's supplier base during its founding years to retail partners operating under FEBA-harmonised donation protocols. The eventual clarification through Law 49/2024 has begun to unlock new categories of surplus generators, including HoReCa operators now required to explore food donation as a primary waste avoidance strategy.

Second, the absence of a dedicated public co-financing mechanism shapes the operational configuration of BRAC in concrete ways. In practice, the organisation fulfils a core social function for the Cluj community, providing substantial services that effectively support the local administration by improving the living conditions and food security of vulnerable residents. From this perspective, it would be both logical and efficient for local authorities to allocate resources for the development of the food bank's infrastructure, for example by providing land or premises for a modern logistics warehouse; however, this has not materialised, leaving BRAC to absorb alone the pressure of growth.

Without access to national infrastructure grants or local in-kind support, the organisation has been unable to expand cold-chain storage capacity at a pace commensurate with donation volume growth: redistributing 1,900 tonnes in 2025 from a single warehouse staffed by ten people represents a productivity level that is functionally unsustainable beyond a certain threshold and generates structural risks for food safety compliance when handling temperature-sensitive products.

Third, the absence of interministerial coordination between Romania's Ministries of Agriculture, Environment, Health, and Social Affairs produces operational frictions visible at the interface between food safety regulations, food waste legislation, and social assistance frameworks.

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This regulatory fragmentation increases administrative burden, prolongs onboarding procedures for new donors and partner NGOs, and reduces operational agility. Yet where policy synergies exist — particularly through EU European Social Fund Plus (ESF+) + co-financing and FEBA's advocacy for rights-based food banking — they provide the institutional legitimacy and financial floor necessary for minimum operational continuity.

6.2. Food Banks as Policy Entrepreneurs and System Integrators

Beyond their role as operational redistribution actors, food banks in contexts such as BRAC have a demonstrable capacity to function as policy entrepreneurs — organisations that mobilise empirical evidence, cross-sector relationships, and institutional credibility to advocate for policy changes extending beyond their immediate operational mandate (Mintrom & Norman, 2009). This entrepreneurial function operates through three distinct channels. First, data-based advocacy: food banks are among the few civil society organisations in Romania that systematically collect and report granular data on food insecurity, surplus volumes, redistribution flows, and donor behaviour — data that government agencies typically do not produce at this operational resolution. The invitation to co-host the FEBA Data & ESG Summit 2025 in Bucharest is a direct recognition of FBAR's role as a knowledge producer and policy interlocutor within the European food banking governance network (FEBA, 2025).

Second, cross-sector network brokering: food banks occupy a structurally unique position at the intersection of the private sector, civil society, and public administration — enabling them to function as system integrators capable of aligning the interests, resources, and operational capacities of otherwise disconnected sectors around shared food waste reduction and food security objectives. In Romania, BRAC has cultivated partnerships with local municipalities for volunteer mobilisation, with universities for food safety training and research collaboration, and with corporate donors for ESG co-reporting. Third, innovation piloting: food banks are, by operational necessity, pragmatic innovators.

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The food hub model piloted by FEBA members — integrating surplus food management with community services, employment creation, and circular economy functions — has been proposed as a replicable urban policy instrument, and Romanian food banks are positioned to pilot analogous innovations in CEE contexts, generating evidence for policy adaptation grounded in the specific realities of transition economies (FEBA, 2025; Reuter et al., 2021).

6.3. Towards More Circular and Resilient Agri-Food Systems

The COVID-19 pandemic provided a stress test for food systems globally and demonstrated the critical role of food banks as resilience infrastructure. A multiple case study of European food banks during the first year of the pandemic found that, despite severe operational disruptions, food banks were able to redistribute significantly higher volumes owing primarily to organisational innovation: new supply chain strategies, restructured internal operations, and rapid activation of new public-private partnerships (Reuter et al., 2021). Crucially, the study found that food banks' pre-existing multi-stakeholder networks were the primary determinants of pandemic resilience — directly relevant to BRAC, whose network of 170 partner NGOs and established retail partnerships enabled rapid scaling in response to crisis-driven surge demand. In CEE more broadly, research on regional economic resilience has shown that the ability to absorb shocks correlates strongly with the density of local institutional networks — precisely the social capital that food banking organisations build through their daily operations (Brada et al., 2021).

Looking beyond resilience to transformation, the integration of food banks into circular agri-food systems requires deliberate expansion of operational scope in three directions. First, partnership with agri-food by-product valorisation chains — linking food banks to processors, distilleries, dairies, and produce markets — would expand the biological resource base available for redistribution and processing. Second, integration with urban food waste management infrastructure — selective collection systems, composting, anaerobic digestion, urban food hubs — would embed food banks within the closed-loop nutrient cycles that characterise circular city food systems.

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Third, deeper collaboration with farmers, agricultural cooperatives, and local food systems actors — channelling harvest surpluses and culls directly into food bank redistribution chains — would align food banking with short supply chain development agendas, contributing simultaneously to rural producer resilience, urban food security, and the reduction of agricultural food losses. Romania's relatively high proportion of small and subsistence farming households represents an underexplored resource base for food banking, and the development of farm-to-food-bank collection protocols, supported by digital traceability tools and appropriate public incentives, would represent a significant circular economy innovation in the Romanian agri-food system.

**CONCLUSIONS AND POLICY/RESEARCH
IMPLICATIONS**

This chapter has examined the operational models and policy frameworks governing food banks in Central and Eastern Europe, with particular focus on Romania and BRAC as an empirical case study, producing four sets of converging findings. First, the classical charity food bank model has delivered measurable social value at scale — FBAR's redistribution of over 39,000 tonnes of food to more than 325,000 beneficiaries — while operating at the structural margins of the circular economy, recovering value from food surplus without systematically integrating the full spectrum of by-product and secondary surplus streams available within the agri-food system. Second, the policy environment in CEE countries remains insufficiently aligned with the operational realities and scaling potential of food banking organisations: legislative fragmentation, inconsistent fiscal incentives, absent interministerial coordination, and chronic underfunding of redistribution infrastructure collectively constrain food banks below their potential contribution to national food waste reduction targets and to the EU Green Deal's Farm to Fork objectives.

Third, the BRAC case study demonstrates that even under these structural constraints, a well-governed regional food bank can achieve exceptional performance — growing from 65 to 1,900 tonnes redistributed in six years, building a partner network of 170 NGOs, reaching 37,000

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beneficiaries, and generating an estimated environmental contribution of over 6,000 tonnes of CO₂ equivalent avoided in 2025 alone.

Fourth, the conceptual continuum from charity food bank to hybrid model to circular social enterprise — articulated across the dimensions of governance, revenue streams, role in circularity, and beneficiary empowerment — provides an analytically useful framework for mapping food bank developmental trajectories and identifying the interventions required at each stage. The hybrid model represents the most immediately achievable step for organisations such as BRAC; the circular social enterprise represents the strategic horizon aligning food banking with European food governance transformation ambitions.

Beyond the immediate policy and operational implications, the findings of this chapter also open several avenues for future research. Comparative and longitudinal studies across CEE countries could clarify how different policy mixes and welfare regimes shape the evolution of food bank models over time. Further work is needed to assess the circular economy potential of hybrid configurations such as food bank–social supermarket systems and by-product processing hubs, including their nutritional, environmental, and economic performance. Finally, digitalisation and data governance in food banking – from traceability platforms to ESG reporting – merit dedicated investigation, both as enablers of efficiency and as new sites of power and accountability in agri-food systems.”

Policy Recommendations for CEE Countries

Drawing on the theoretical framework, policy analysis, and empirical evidence presented in this chapter, five evidence-based recommendations are directed at national governments, EU institutions, and food banking networks operating in CEE contexts:

(1) Clarify and harmonise the legal framework for food donation: Member States should adopt clear, single-document national food donation guidelines consolidating food safety, liability, VAT treatment, and traceability requirements for both donors and redistribution operators, accompanied by national awareness campaigns for retail, HoReCa, and food processing operators.

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(2) Strengthen fiscal incentives for food donation: tax incentive structures should ensure that the total cost of donating surplus food does not exceed the cost of disposal for food business operators, through enhanced corporate income tax deductions, VAT exemptions, and logistics cost subsidy mechanisms.

(3) Establish dedicated public co-financing schemes for food bank infrastructure: national governments should introduce multi-annual co-financing programmes specifically targeting food bank cold-chain infrastructure, digital traceability systems, warehouse capacity, and vehicle fleet development, recognising food bank infrastructure as a strategic public good generating quantifiable value in CO₂ emissions avoided, social assistance cost reduction, and public health improvement.

(4) Integrate food banks into national food waste reduction strategies: food banks should be formally designated as strategic actors within national food waste reduction plans under SDG 12.3 and the EU Farm to Fork targets, with a single interministerial coordination body mandated to oversee food donation policy and remove regulatory friction between ministerial domains.

(5) Support the transition from charity to hybrid circular models: through social enterprise legal frameworks, urban planning provisions incorporating food bank infrastructure, and agricultural policy support for farm-to-food-bank surplus donation channels, including collection cost subsidies for small and medium agricultural producers.

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