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Optimising Local and Imported Poultry Feed Formulation in West Papua, Indonesia: Integrating Supply Chain Analysis and Least- Cost Diet Formulation

A thesis presented in partial fulfilment of the requirements for the degree of
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Abstract

Poultry production in Indonesia contributed to the nation's economy and food security. The poultry sector provides employment all around Indonesia and supplies 65% of the nation's animal protein, including eggs and meat. This effect extends to the development of poultry sectors in areas like West Papua Province in the eastern part of Indonesia. However, the challenges in the poultry industry are that the total production costs of farms come from the feed costs and the feed supply. The source of feed ingredients in West Papua Province comes from domestic trading within Indonesia or imports, leading to price fluctuations, high production costs, and supply chain vulnerabilities. Subsequently, formulating broiler and layer chicken diets with locally produced and imported ingredients could help lower feed costs and support sustainability. By examining the price and accessibility of locally produced, domestically traded, and imported ingredients for the formulation of poultry diets in West Papua Province, this thesis explores the supply of livestock feed.

Linear programming was utilised to formulate poultry diets by incorporating ingredient nutrient composition values against the poultry nutrient requirements. The data on the nutritive values and the costs were obtained from secondary sources, including academic literature, industry reports and statistics, government publications, and online market data. Linear programming has formulated 25 poultry diets utilising both local and imported ingredients without violating necessary nutrient requirements. In exploring supply chain vulnerabilities, a sensitivity analysis was performed on these initial diets. Three additional constraints were introduced by setting a zero-inclusion level for maize only, soybean meal only, and both ingredients. These constraints were applied to each representative broiler and layer diet. The findings in this research were that linear programming found infeasible solutions when formulating the selected broiler diet under these scenarios, demonstrating the dependence of maize and soybean meal. However, linear programming was able to formulate three-layer diets using partly local and imported ingredients, though these were more costly than the original diet. Under the sensitivity analysis scenarios, this research found that even though the initial representative layer diet also partly relied on maize and soybean meal, the initial layer diet could still partially substitute maize and soybean meal with local

ingredients. Accordingly, the sensitivity analysis revealed the supply chain vulnerability of the maize and soybean meal, which underscores the cost-effectiveness of poultry production.

Therefore, this research provides recommendations in optimising poultry diet formulation, including allowing ingredient flexibility, substitution and diversification, strengthening supply chain partnerships, developing strategies for storage and infrastructure development, and proposing government support and policy can optimise feed formulations. Integrating supply chain analysis and least-cost diet formulation underscores the significance of the supply chain of feed ingredients in the region. Regional agricultural and farm enterprises, the government and the poultry industry, and economic sustainability in West Papua Province or regions in similar settings would benefit from the results of this research.

Keywords: supply chain, least-cost diet formulation, linear programming, Manokwari, West Papua Province, Indonesia

Preface

This thesis was driven by my experience managing a small farm business, where I have come across the irregular availability of feed during certain periods in Manokwari or across Papua Island in general. The feed shortages motivated me to explore diet development and understand how the logistics and supply chains of the feed industry operate. From this perspective, the thesis acts as a bridge between business and applied animal science. It may not be the perfect example, but if you have ideas to improve it, I am open to collaboration, networking, or discussion at mfachdansemahu@gmail.com. I would be glad to connect. Thank you for your interest; everyone is welcome.

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Table of Contents

Table of Contents

Abstract	i
Preface	iii
Acknowledgement	iv
List of Figures	viii
List of Tables.....	ix
List of Abbreviations.....	x
Chapter 1: Introduction	1
1.1 Research Topic.....	1
1.2 Aim of the Research.....	5
1.3 Research Questions	5
1.4 Research Objectives.....	5
1.5 Potential Contribution to Knowledge	6
1.5.1 Regional Agricultural and Farm Enterprises	6
1.5.2 Government and Poultry Industry	6
1.5.3 Economic Sustainability	6
1.6 Thesis Structure	7
Chapter 2: Literature Review	8
2.1 Supply Chain Management.....	8
2.1.1 Sourcing of Ingredients	12
2.1.2 Transportation and Logistics.....	12
2.1.3 Storage and Inventory	13
2.2 Poultry Nutrition.....	14
2.2.1 Energy	14
2.2.2 Carbohydrates	16
2.2.3 Protein and Amino Acids	16
2.2.4 Lipids	17
2.2.5 Minerals and Vitamins	18
2.2.6 Water.....	19
2.3 Selected Feed Ingredients.....	20
2.3.1 Maize.....	20
2.3.2 Wheat.....	20
2.3.3 Rice Bran.....	21
2.3.4 Cassava Root Meal	21

2.3.5 Soybean Meal	22
2.3.6 Meat and Bone Meal	22
2.3.7 Fish Meal	23
2.3.8 Copra Meal	24
2.3.9 Black Soldier Fly Larvae	24
2.3.10 Cassava Leaf Meal.....	25
2.3.11 Palm Oil	26
2.3.12 Limestone, Dicalcium Phosphate, and Tricalcium Phosphate.....	26
2.3.13 Lysine, DL-Methionine, and L-Threonine	28
2.3.14 Sodium Chloride and Sodium Carbonate	28
2.3.15 Mineral and Vitamin Premixes	29
2.4 Ration Formulation.....	29
2.5 Linear Programming	30
2.6 Conclusion.....	37
2.7 Gaps in Literature	37
Chapter 3: Research Methods	38
3.1 Research Aim and Objectives.....	38
3.2 Research Design	38
3.3 Study Area Selection.....	40
3.4 Data Collection	41
3.5 Data Analysis	52
3.6 Sensitivity Analysis.....	52
3.7 Validity, Reliability, and Transparency.....	53
3.7 Ethical Considerations	53
Chapter 4: Supply Chain of Livestock Feed Ingredients	54
4.1 Sourcing of Livestock Ingredients, Transportation and Logistics	54
4.1.1 Maize.....	56
4.1.2 Wheat.....	56
4.1.3 Rice Bran.....	57
4.1.4 Cassava Root Meal.....	57
4.1.5 Soybean Meal	58
4.1.6 Meat and Bone Meal	58
4.1.7 Fish Meal	59
4.1.8 Copra Meal	59
4.1.9 Black Soldier Fly Larvae	60

4.1.10 Cassava Leaf Meal.....	60
4.1.11 Palm Oil	61
4.1.12 Limestone	61
4.1.13 Dicalcium Phosphate and Tricalcium Phosphate.....	62
4.1.14 Lysine, DL-Methionine, and L-Threonine	62
4.1.15 Sodium Chloride and Sodium Carbonate	63
4.1.16 Mineral and Vitamin Premixes	64
4.2 Storage and Inventory.....	64
4.3 Conclusion	65
Chapter 5: Results	66
5.1 Broiler Diet Formulations Results.....	66
5.2 Layer Diet Formulations at the Lower Limit Energy Requirements Results	69
5.3 Layer Diet Formulations at the Upper Limit Energy Requirements Results	72
5.4 Sensitivity Analysis Results.....	75
Chapter 6: General Discussion	78
6.1 Nutrient Composition and Supply Chain Considerations	79
6.2 Feed Formulation and Supply Chain Implications.....	81
Chapter 7: Recommendations and Conclusion	84
7.1 Recommendations.....	84
7.1.1 Offering Ingredient Flexibility, Substitution, and Diversification.....	84
7.1.2 Strengthening Supply Chain Partnerships.....	84
7.1.3 Developing Strategies for Storage and Infrastructure Development	85
7.1.4 Proposing Government Support and Policy	86
7.1.5 Undertaking Research on Ingredients Digestibility and Nutritive Values	86
7.2 Conclusion.....	87
7.3 Limitations.....	88
7.4 Future Research Implications	88
References	89
Appendices	98

List of Figures

Figure 1: West Papua Province in Indonesia	4
Figure 2: West Papua Province with Regencies	4
Figure 3: A Standard Form of the Model	31
Figure 4: Feasible Region	32
Figure 5: Feasible Region, Feasible Solutions and Infeasible Solutions	33
Figure 6: Multiple Solutions	33
Figure 7: No Feasible Solutions; therefore, No Optimal Solutions	34
Figure 8: Unbounded Solutions	35
Figure 9: Five CPF Solutions	36
Figure 10: Shipping route to West Papua Province in Indonesia	55
Figure 11: Shipping route to West Papua Province.....	55

List of Tables

Table 1: Ingredients Nutrient Composition	44
Table 2: Dietary Requirements for Broilers	47
Table 3: Ingredient Inclusion Levels for Broilers	48
Table 4: Dietary Nutrient Requirements for Layers at the Lower Energy Limit	49
Table 5: Ingredient Inclusion Levels for Layers at the Lower and Upper Energy Limits	50
Table 6: Dietary Requirements for Layers at the Upper Energy Limit.....	51
Table 7: Broiler Diet Formulations	67
Table 8: Nutritive Values of Broiler Diet Formulations.....	68
Table 9: Layer Diet Formulations at the Lower Limit Energy Requirement.....	70
Table 10: Nutrient Profile of Layer Diet Formulations at the Lower Limit Energy Requirement	71
Table 11: Layer Diet Formulations at the Upper Limit Energy Requirement.....	73
Table 12: Nutrient Profile of Layer Diet Formulations at the Upper Limit Energy Requirement	74
Table 13: Sensitivity Layer Diet Formulations	76
Table 14: Nutritive Values of Sensitivity Layer Diet Formulations	77
Table 15: Ingredients availability and the usage of the ingredients in the least-cost diet formulations.....	78

List of Abbreviations

AA	Amino Acid
AAs	Amino Acids
ADF	Acid Detergent Fiber
Ala	Alanine
AME	Apparent Metabolisable Energy
AME _n	AME Corrected for Nitrogen
Arg	Arginine
Asp	Aspartic Acid
AvP	Available Phosphorus
BSFL	Black Soldier Fly Larvae
BULOG	Badan Urusan Logistik (The Indonesian National Food Logistics)
CaCO ₃	Calcium Carbonate/Limestone
CaHPO ₄	Dicalcium Phosphate
Ca ₃ (PO ₄) ₂	Tricalcium Phosphate
Ca	Calcium
cal	Calories
CF	Crude Fibre
Cl	Chloride
CLM	Cassava Leaf Meal
CM	Copra Meal
Co	Cobalt
CP	Crude Protein
CPF	Corner-Point Feasible
Cr	Chromium
CRM	Cassava Root Meal
Cys	Cysteine
Cu	Copper
DCP	Dicalcium Phosphate
DE	Digestible Energy
DKI JKT	Daerah Khusus Ibukota Jakarta Province (Provinsi Daerah Khusus Ibukota Jakarta)
DL-Methionine	Dextro Levo Methionine
DM	Dry Matter
EAA	Essential Amino Acids
EJ	East Java Province
FAO	Food and Agriculture Organization of the United Nations
FCR	Feed Conversion Ratio
Fe	Iron
FM	Fish Meal
GE	Gross Energy
Glu	Glutamic Acid
Gly	Glycine
GRDP	Gross Regional Domestic Product
His	Histidine
HU	Haugh Unit

I	Iodine
IDR	Indonesian Rupiah
Iso	Isoleucine
J	Joules
JKT	Jakarta
K	Potassium
kcal	Kilocalorie
kJ	Kilojoules
Leu	Leucine
LiSt	Limestone
Lys	Lysine
L-Lys	Levo Lysine
L-Threonine	Levo Threonine
LP	Linear Programming
MAI	Ministry of Agriculture of Indonesia (Kementerian Pertanian Indonesia)
MBM	Meat and Bone Meal
Mcal	Mega calorie
ME	Metabolisable Energy
ME _n	Metabolisable Energy Nitrogen-Corrected
Met	Methionine
Mg	Magnesium
MJ	Megajoules
MKS	Makassar
MKW	Manokwari
Mn	Manganese
Mo	Molybdenum
MP	Mineral Premix
Mt	Metric ton
N	Nitrogen
Na	Sodium
NaCl	Sodium Chloride/Salt
Na ₂ CO ₃	Sodium Carbonate
NE	Net Energy
NEAAs	Nonessential Amino Acids
NRC	National Research Council
NZD	New Zealand Dollar
OEC	The Observatory of Economic Complexity
P	Phosphorus
Phe	Phenylalanine
PO	Palm Oil
Pro	Proline
RHS	Range Hand-Side
RB	Rice Bran
S	Sulphur
SBM	Soybean Meal

SBY	Surabaya
SCM	Supply Chain Management
Se	Selenium
Ser	Serine
SID	Standardised Ileal Digestibility
SRG	Sorong
SS	South Sulawesi
SWP	Southwest Papua
Statistics Indonesia	Statistics Indonesia (Badan Pusat Statistik Indonesia)
Statistics WP	Statistics West Papua Province (Badan Pusat Statistik Provinsi Papua Barat)
t	Ton
TCP	Tricalcium Phosphate
Thr	Threonine
TME	True Metabolisable Energy
Tyr	Tyrosine
UK	United Kingdom
USA	United States of America
USD	United States Dollar
USDA	United States Department of Agriculture
Val	Valine
Vitamin B1	Thiamine
Vitamin B2	Riboflavin
Vitamin B3	Niacin or Nicotinic Acid
Vitamin B5	Pantothenic Acid
Vitamin B6	Pyridoxine
Vitamin B7	Biotin
Vitamin B9	Folacin or Folic Acid
Vitamin B12	Cyanocobalamin
Vitamin C	Ascorbic Acid
Vitamin E	Tocotrienols
VP	Vitamin Premix
WJ	West Java Province (Provinsi Jawa Barat)
WP	West Papua Province (Provinsi Papua Barat)
Zn	Zinc

Chapter 1: Introduction

1.1 Research Topic

The poultry industry in Indonesia has contributed to the country's food security and economic growth. The poultry industry provides over 12 million jobs for people, possesses an estimated worth of more than 34 billion USD (United States of America Dollar), and supplies 65% of Indonesians' animal protein, including eggs and meat production (Ferlito & Respatiadi, 2018). Employment in the poultry industry expands across the nation, including the eastern side of the country. Nurhasan et al. (2022) stated that this effect extends to the development of poultry sectors in the Manokwari Regency (MKW), the capital city of West Papua Province (WP) or Provinsi Papua Barat in the eastern part of Indonesia.

At the coordinates of 124°-132° East Longitude and 0°-4° South Latitude, WP is situated on the peninsula on the western side of Papua Island (Statistics WP, 2025). The exact location of WP can be seen in Figure 1. Consisting of seven regencies or municipalities and 96 districts, and 969 villages or subdistricts, WP covers a total area of 60,275.33 square kilometres. Figure 2 provides details of the regencies within WP. The total population of WP is approximately 587,650 people. The city of MKW, the capital, has the largest population at around 208,000, while Manokwari Selatan Regency has the smallest, with about 39,000 residents (Statistics WP, 2025).

The working age for the labour population in WP is people aged 15 years and above (Statistics WP, 2025). According to Statistics WP (2025), WP's unemployment rate was at 4.13% detailing about 290,000 employed and 12,000 unemployed. The three leading sectors in WP include agriculture, forestry and fishery (120,703 people); wholesale and retail trade, motor vehicles and remediation activities (44,287 people); and social security, defence, and public administration (41,921) (Statistics WP, 2025).

Allo et al. (2022) stated that the Gross Regional Domestic Product (GRDP) is derived from economic activities across different sectors in a certain period, and manufacturing was the main contributor to the GRDP of WP from 2015 to 2019, covering an average of about 26%. Based on Statistics WP (2025), in 2024, WP reached 76,177.48 billion IDR (Indonesian Rupiah) of GRDP. If converted to the exchange rate for 9,551 IDR equals 1 NZD (New Zealand Dollar)

on 23 August 2025, 03:06 UTC, the WP's GRDP equalled 7.98 billion NZD. Allo et al. (2022) stated that over the last ten years, the WP's GRDP is derived from the agriculture, forestry and fisheries, providing an average of 10.75% per year. Allo et al. (2022) and Statistics WP (2025) agree that the biggest employment in WP is in the agriculture, forestry and fisheries sector. However, the province remains facing low food security (Iyai et al., 2023; Nurhasan et al., 2022). In response to this matter, improving the poultry production may improve food security. Especially, with the rising trend for poultry products, including chicken meat and eggs (Nurhasan et al., 2022), understanding the production of the poultry industry is crucial.

However, the poultry industry is facing challenges, as about 70% of a farm's total operating costs are attributed to feed costs (Alhotan, 2021; Arizona et al., 2023; Heidari et al., 2021) and feed supply (Irawan et al., 2022). Many formulated chicken feeds and feed ingredients are generally sourced from other regions of Indonesia or overseas, leading to high production costs, price fluctuations, and supply chain vulnerabilities for farm businesses (Rapi et al., 2020). As a sequence, utilising locally produced ingredients in formulating chicken diets may lessen the farm production costs. Iyai et al. (2023) stated the leading local commodities in WP are nutmeg, palm oil, cocoa, coffee, sweet potato, cassava, and sago, some of which can be incorporated into feed ingredients for livestock development. Consequently, partially or fully utilising local commodities can support local agriculture, promote sustainability practices, and reduce feed costs (Abdollahi & Ravindran, 2017). Thus, creating a diet that uses local ingredients can reduce price vulnerability and might lead to a financially sustainable poultry industry in WP.

This research incorporates diet formulations using ingredients sourced from local producers, domestic and imported suppliers. While the nutritional contents can influence the quality of livestock feeds (Leeson & Summers, 2005), the selected ingredients include energy sources, carbohydrates, protein and amino acids, lipids, minerals and vitamins. The range of ingredients aligns with Heidari et al. (2021), stating that the goal of diet formulation is to meet the nutrient requirements with the appropriate mix of quality and quantities of diverse ingredients. Ingredients used in this research are maize, wheat, rice bran (RB), cassava root meal (CRM), soybean meal (SBM), meat and bone meal (MBM), fish meal (FM), copra meal (CM), black soldier fly larvae (BSFL), cassava leaf meal (CLM), palm oil (PO), calcium carbonate

or limestone (CaCO_3), dicalcium phosphate (DCP) (CaHPO_4), tricalcium phosphate (TCP) ($\text{Ca}_3(\text{PO}_4)_2$), amino acids (AAs) like lysine, DL-methionine (DL refers to the presence of D- and L- isomers for Dextro Levo methionine), L-threonine (L refers to the presence of L- isomers for Levo threonine), salt or sodium chloride (NaCl), sodium carbonate (Na_2CO_3), mineral premix and vitamin premix. Therefore, optimising a chicken diet with a sound composition from imported and locally produced ingredients can support livestock performance while meeting their nutritional requirements.

Furthermore, the price and availability of ingredients influence the composition of poultry diets, suggesting that the supply chain is a critical element when formulating livestock diets. Supply chain management (SCM) encompasses all the management and planning activities from sourcing and procurement to logistics and conversion management of goods (Ronaldo, 2020). The supply chain involves meeting the needs of ingredients in some regions and distributing them from the producer to the consumer level (Itang et al., 2022). Accordingly, SCM is necessary in formulating diets and enhancing sufficiency and cost-effectiveness.

Examining the supply chain of livestock feed ingredients in WP, Indonesia, is necessary to maximise the cost-effectiveness of the diet formulation with the utilisation of linear programming (LP) and ingredient composition sheets or feedstuff matrix on Microsoft Excel. Optimising poultry diets by utilising LP and the standardised ileal digestibility (SID) values in the ingredient composition sheets can address the cost and nutritional balance. Standardised ileal digestibility values are standard to measure amino acids (AAs) digestibility (Bloxham et al., 2023), measured by the difference of AAs consumed by animals and recovered from the digesta in the ileum, correcting for basal endogenous AAs losses. The SID values of AAs in feedstuff or feed ingredients are critical and have been recorded in databases for nutritionists to utilise when formulating diets based on digestibility (Bloxham et al., 2023). The diets incorporating SID values result in increased nitrogen (N) absorption, leading to reduced pollution and dietary costs (Bloxham et al., 2023). Consequently, using the SID data basis for feed ingredients is necessary to create cost-effective diet formulation and optimise growth performance through LP modelling.

Thus, while the stability and reliability of ingredients may affect the least-cost diet formulations, this research promotes integrating the supply chain into poultry diets. The research offers a business perspective and the utilisation of a mathematical optimisation tool. Subsequently, in optimising local and imported poultry feed formulations, integrating supply chain analysis into diet formulations is necessary to meet poultry nutrient requirements while achieving sustainability, economic benefits, and cost efficiency in WP, Indonesia.



Figure 1. West Papua Province in Indonesia (Nordnordwest, 2024).



Figure 2. West Papua Province with regencies (OFO Maps, 2024).

1.2 Aim of the Research

This research aims to investigate the supply chain of livestock feed ingredients by considering the cost, dependability, and availability of local and imported ingredients in MKW, WP, Indonesia. This research provides an approach incorporating LP and ingredient nutrient composition values in optimising diet formulation for their cost-effectiveness and nutritional content in broiler and layer chicken diets. The results are to indicate which ingredients can be used in chicken diet formulation and propose suggestions to enhance the efficiency of poultry production and sustainability in WP, Indonesia.

1.3 Research Questions

1. Which key factors - price, availability, transportation, and dependability- have an impact on the livestock feed components supply chain in MKW, WP, Indonesia?
2. How may LP, ingredient nutrient composition, and supply chain analysis be combined to satisfy the nutritional needs of poultry, ingredient availability, and the related costs in creating livestock diet formulation in MKW, WP, Indonesia?
3. Does using locally produced and imported ingredients in feed formulations achieve the least-cost diet and sustainability in MKW, WP, Indonesia?

1.4 Research Objectives

1. To investigate the supply chain for livestock feed ingredients with a focus on cost, availability, transportation, and dependability in MKW, WP, Indonesia.
2. To integrate LP, ingredient nutrient composition, and supply chain analysis in optimising livestock diet formulation based on poultry nutrient requirements, ingredient availability, and related costs in MKW, WP, Indonesia.
3. To assess the profitability and cost-effectiveness of locally produced and imported ingredients in feed formulations in order to lessen reliance on imported ingredients in the supply chain and sustainability in MKW, WP, Indonesia.

1.5 Potential Contribution to Knowledge

There is a wide range of areas where this research can add knowledge. This study offers essential insights into poultry diets and supply chain issues, which could have unpredictable effects on society. The findings may impact various groups or organisations, including businesses, animal science practitioners, and policymakers.

1.5.1 Regional Agricultural and Farm Enterprises

If the locally produced ingredients are able to affect poultry productivity or be incorporated into the chicken diets of local producers, the local farmers may gain beneficial outcomes. The reduced feed costs could be advantageous to them and boost profitability. Furthermore, the farmers have more choices of poultry feeds along with imported factory feeds. This can increase the farm enterprise's profitability and lessen dependency on imported feed from neighbouring islands (Khempaka et al., 2022).

1.5.2 Government and Poultry Industry

The potential results could inform related government departments to promote local ingredients as a consideration for constructing a feed factory. In MKW, WP, there has been a plan to build a feed factory, including laying chicken feed (Antara, 2022). This possible finding turns the idea of building a chicken feed factory into a reality in MKW. The poultry industry may undergo an enormous transition if the local ingredient mix proves to be profitable and successful. People and farm enterprises are likely to choose goods manufactured using local ingredients if the cost of production is reasonable and the quality is comparable to imported feeds.

1.5.3 Economic Sustainability

The results of the study may have implications for sustainability and economic growth. Compared to imported feeds, local ingredients could be less expensive (Wardhany et al., 2017). If the government or other investors would like to invest in this promising potential feed production, the investment in feed production could generate employment opportunities and strengthen local economies, while supporting local agriculture with the relevant ingredients. Moreover, it aligns with sustainability practices by utilising local ingredients and reducing the carbon footprint of imported feed (Olarotimi & Adu, 2017).

1.6 Thesis Structure

This study comprises seven chapters. Chapter one (this chapter) introduces the thesis, background, problem statements, research aims, research questions, objectives, and limitations, and provides a brief overview of poultry, agricultural industries, and their supply chain in WP, Indonesia. Chapter two reviews the literature on supply chains, poultry nutrition, ration formulation, and the application of LP and ingredient nutrient composition in diet formulation. Chapter three outlines the research methods. Chapter four discusses the region's supply chain of livestock feed ingredients and their availability. Chapter five presents the results of least-cost diet formulations. Chapter six offers a general discussion of the formulated diets and their supply chain implications. Lastly, chapter seven provides recommendations, limitations and future research implications, and summarises the results of this study.

Chapter 2: Literature Review

Producing a chicken diet while addressing the supply chain of contained ingredients influences the formulation. Elements like the nutritional contents, the tools in formulating the diets, and the SID are used to provide vital information to optimise the ratio and efficiency in the diet formulation (Cheeke, 2005; Dryden, 2008; Pond et al., 2005). This chapter investigates the literature on SCM, poultry nutrition, ration formulation, LP, and their relations to each other in diet formulations.

2.1 Supply Chain Management

In business activities like animal feed production, SCM plays a crucial role. According to Khan and Yu (2019), SCM is the planning and management of activities involving production, sourcing, procurement, conversion, and all logistical management activities from raw materials to fulfil the needs of the final consumers while minimising the cost. Equally, Sibuea et al. (2023) defined SCM as a network of facilities with various functional activities, from purchasing raw materials, converting these materials into final products, and distributing the final products to consumers while reducing costs.

Many studies have addressed the possibility that SCM in creating diet formulations can influence the prices of the feed ingredients. Csikai (2011) stated that the SCM addresses potential issues and risks during the supply and distribution of feed ingredients to lower costs and optimise profits. Itang et al. (2022) mentioned that the SCM can generate a competitive advantage for feed companies by optimising the distribution and sourcing of ingredients. Itang et al. (2022) added that the SCM could reduce the full cost of production. The coordination of the ingredients, from post-harvesting at the farm level to storage and delivery to end consumers, can add to a company's competitiveness (Itang et al., 2022). Reducing uncertainty and inventory levels, the delivery of quality ingredients at reasonable costs, and good engagement with business partners across the supply chain of goods can lead to successful SCM as one system (Itang et al., 2022). Irawan et al. (2022) confirm that integrating feed formulation, production, and SCM promotes optimum feed raw-ingredient consistency, cheaper raw ingredients, more accurate planning, better traceability, and improved supplier performance. Sibuea et al. (2023) stated that the objective of SCM is to optimise business

performance in generating product value by allocating as small or as limited costs as possible. SCM is meant to reduce costs and capital but improve service for end consumers by reducing the uncertainty to improve the supply chain performance (Sibuea et al., 2023). Thus, integrating the supply chain into diet formulation can affect the prices of the feed ingredients.

There are a few crucial activities in the SCM process for feed formulation. Khan and Yu (2019) stated that these activities include the delivery of products by sourcing raw ingredients, assembling and manufacturing, account tracing and warehousing, order entering and managing, distributing, supplying to the producer, and the information technology systems. The activities involved collaboration and coordination with all supply chain partners, including suppliers, manufacturers, warehouses, stores, third-party service providers and consumers (Khan & Yu, 2019). Ronaldo (2020) added that SCM synchronises and combines these activities to stay aligned and engage with all related parties. Understanding these crucial activities can address early errors and mitigate complications.

Identifying the supply chain process involving various actors or suppliers at different stages can help detect delays and a reduction in the quality of ingredients. Irawan et al. (2022) indicated that in the formulation process, one major issue is that the availability and demand for ingredients do not align. Integrated feed formulation and production management are critical in investigating this issue by providing planning of when to order ingredients at a lower cost, assisting in a consistent supply of ingredients, and maintaining traceability of the ingredients (Irawan et al., 2022). Applying SCM enhances this situation since this process requires many actors at different phases, including the final actor: customers, then sellers, storage facilities, distributors, suppliers, and the ingredient producers (Itang et al., 2022). Each of these actors takes a part in the efficiency and effectiveness of the SCM process, ensuring the overall ingredient quality. Better-quality ingredients promote better-quality feed formulation with minimum risks, for instance, aflatoxin in domestic corn (Itang et al., 2022). Subsequently, early detection through various actors in the SCM process can prevent worse scenarios and allow actions for improvement.

Some key factors can benefit diet formulation and supply chain quality management. Csikai (2011) highlighted the benefits of integrating diet formulation and supply chain quality management, including consistency of ingredient quality and safety, accuracy in production

planning, supplier quality assurance, and better raw material purchasing planning at specific prices and certain quality. Other factors include operations and logistics management, time savings in formulating diets with the integration of new feed ingredients, documentation, traceability and quality management, and financial benefits such as least-cost diets with a better negotiating position at suppliers (Csikai, 2011). While integrating diet formulation and supply chain quality management enhances the logistics, quality and safety of ingredients, it can also promote financial benefits.

In formulation, the quality of ingredients is crucial; competitive advantage can be gained from the moment of the post-harvesting process for certain ingredients, such as corn (Itang et al., 2022), to distribution channels. A feed mill is where all ingredients are processed through grinding, mixing, pelleting, and packaging into livestock feeds (Aminuddin & Okdinawati, 2023). However, one of the most common issues is the lack of storage for raw ingredients and the feeds produced, which leads to feed supply constraints (Aminuddin & Okdinawati, 2023). Consequently, technology is proposed as a powerful tool to support the poultry supply chain by providing accurate information on food and safety standards for livestock production (Aminuddin & Okdinawati, 2023; Cheeke, 2005). Modern post-harvesting methods are necessary to store and transport ingredients while maintaining quality (Itang et al., 2022). When peak seasonal ingredients are available, SCM is essential (Itang et al., 2022). The production company must offer adequate storage and drying facilities to preserve ingredient quality (Itang et al., 2022). Therefore, companies need to evaluate their systems and performance to develop competitive advantages (Itang et al., 2022). Not only does maintaining ingredient quality with proper modern methods and technology benefit diet formulation, but it can also further enhance the competitive advantages of companies.

Expanding the planting area of feed ingredients can improve domestic production of the selected feed ingredients. Itang et al. (2022), for example, suggested that increasing maize production can protect the national maize supply in Indonesia. Along with the protection of maize production, significant efforts are needed, including further innovation to improve maize quality and yield, and to reduce ingredient production costs (Itang et al., 2022). Consequently, SCM is necessary to identify and evaluate ways to enhance the production of feed ingredients. One of the further examples is that there is no overshadowing institution for

maize farmers to produce and market their crops in Simalungun Regency in Indonesia (Sibuea et al., 2023). Meanwhile, the point of SCM is the strong and effective collaboration among farmers, suppliers, collectors, and other actors in SCM processes (Sibuea et al., 2023). In the case of Simalungun Regency, SCM is not correctly implemented, where farmers or businesses carry out individual production and market their products (Sibuea et al., 2023).

Accordingly, policies can support running a successful supply chain. Policies in the poultry supply chain are made to secure animal welfare, food safety, and sustainable development in the poultry industry in Indonesia (Aminuddin & Okdinawati, 2023). Concerning improving the final customers of chicken meat in Indonesia, specific processes in the supply chain have been tailored to Indonesian policy, including dietary nutrition and the slaughter process (Aminuddin & Okdinawati, 2023). A poultry farm is an agricultural establishment in which poultry are taken care of for commercial purposes, such as egg and meat production (Aminuddin & Okdinawati, 2023). The poultry trading house plays an important role in facilitating the sale and purchase of poultry products among retailers, distributors, processors, and farmers (Aminuddin & Okdinawati, 2023). A slaughterhouse is a facility where birds are slaughtered and processed into meat products for human consumption (Aminuddin & Okdinawati, 2023). This condition has shown that understanding and implementing the right policies can influence customer preferences to ensure the flavour and texture of poultry meat and eggs (Aminuddin & Okdinawati, 2023).

Moreover, the increase in the human population makes the livestock's contribution to the food production chain more substantial, including the practice of animal rights, animal welfare, and agricultural waste management (Cheeke, 2005). These people require food from animal production and agriculture (Cheeke, 2005; Pond et al., 2005). Cheeke (2005) acknowledged that how animals are fed, and the environmental concerns have increased in relevance, including how the practice of agricultural waste management can incorporate crop residues as feed ingredients. Correspondingly, since the principle of using ingredients in diet formulation is not to compete with human needs, the policy related to the use of the ingredients must meet the world's food production while still being available for animal feed ingredients (Cheeke, 2005; Pond et al., 2005).

2.1.1 Sourcing of Ingredients

Sourcing ingredients to formulate poultry feed in WP faces significant challenges because of the dependency on trading from other regions in Indonesia, importing from other countries and the limited production of selected ingredients in WP. The high cost of transportation and the dynamic global prices of various ingredients affect the cost (Rapi et al., 2020). Correspondingly, the use of technology can promote scalable solutions, improve efficiency, and enhance the accuracy supply of ingredients (Aminuddin & Okdinawati, 2023).

Aminuddin & Okdinawati (2023) further mentioned that a better technology should be applied to feed mill production that involves processing raw ingredients to create livestock feed ingredients. This feed mill production process includes grinding, mixing, pelleting, and packaging (Aminuddin & Okdinawati, 2023). Selecting suppliers is crucial as the ingredients delivered can come from domestic trade and international markets. Evaluating the supplier performance of ingredients delivered can be utilised to measure performance and improvement, and to minimise frequent risks (Wahyuni et al., 2021). According to Wahyuni et al. (2021), the supplier performance for the ingredients delivery criterion evaluates the communication systems, the quality of ingredients, the suppliers' history, guarantee and claim policies, the delivery of ingredients and prices. Hence, sourcing ingredients can mean carefully selecting suppliers for the reliability and price of the selected ingredients.

2.1.2 Transportation and Logistics

Transportation, logistics, and infrastructure are significant issues in WP's livestock formulation supply chain. Logistic planning in WP is vital because of the high cost related to transportation from Java Island to WP (Ksatrya et al., 2018). Many studies have found that the high cost is due to limited infrastructure in the eastern region of Indonesia, including Papua Island (Herliana & Parsons, 2011; Simatupang, 2013). Many selected feed ingredients are sourced from other islands in Indonesia or can be imported from other countries. Therefore, sea transportation in Indonesia is the most cost-effective mode of transportation for the carriage of goods compared to other modes, such as air and land transportation (Zaman et al., 2015).

Concerning WP's limited infrastructure and geographic isolation, logistics and transportation become fundamental aspects of the feed supply chain. Rapi et al. (2020) mentioned that ingredients or goods must transit through several regions in Indonesia before arriving in WP,

which leads to higher costs and logistical delays. Pope et al. (2023) mentioned that if not handled and stored correctly for feedstuffs, vitamin and mineral premixes, delays in logistics and transportation during shipment can result in deterioration, which can impact the goods' quality. White et al. (2021) indicated that imports of maize or feed ingredients occur when there are shortages of feed ingredients, which further complicate logistical concerns in Indonesia. Pope et al. (2023) asserted that a robust supply chain should not only rely on specific modes of transportation but should also include shipping from different regions for each mineral and vitamin. Even though air freight is fast, it is more expensive than sea transportation; sea transportation remains preferable. Subsequently, effective logistics and transportation are fundamental to ensure a reliable supply chain of feeds in WP, involving comprehending proper storage and mode of transportation.

2.1.3 Storage and Inventory

Since WP has few options for transportation and logistics in the region, storage and inventory management can play a crucial role in storing the available feed ingredients throughout the year. Inventory acts as a safety and buffer stock to suppress uncertainties due to fluctuations in delivery time, demand, and supply (Khan & Yu, 2019). Inventory requires handling and storage space (Khan & Yu, 2019). Aminuddin and Okdinawati (2023) addressed that one of the common problems in feed mill production is the need for sufficient storage. Nevertheless, the lack of proper storage facilities in WP poses a challenge due to the limited stockpile of ingredients when there are low prices or high supply. Balancing the stockpile can prevent scarcity or shortages of ingredients (Aminuddin & Okdinawati, 2023). Therefore, acknowledging the utilisation of storage in handling feed ingredients is beneficial in feed mill production.

Warehouses and technology influence the quality of storage and inventory. Simatupang (2013) wrote that warehouses and technology can include a supply system that utilises temperature control. Along with this system, Khan and Yu (2019) agreed that storage can temporarily be where goods wait to be transferred to the next stop. Appropriately, the improvement in storage and inventory can maintain the quality of ingredients along the whole supply chain process based on the ingredients' needs (Simatupang, 2013); even after making the feed, this can ensure the shelf life of the feed. The foremost elements in choosing a storage

system are the effectiveness of using building volume, both horizontal and vertical, the nature and characteristics of the items held and unit loads, stock accessibility, the maintenance of condition and stocks, personnel safety and overall system costs (Khan & Yu, 2019). In storage and inventory management, regular monitoring of the storage and inventory can address issues that arise early (Khan & Yu, 2019; Simatupang, 2013). Thus, retaining the quality of the ingredients can manage storage and inventory.

2.2 Poultry Nutrition

When creating a diet, one should consider the nutrient requirements and the composition of the selected ingredients. Poultry need an easily digested and well-balanced diet for maximum production of meat and eggs (Blair, 2008). Understanding the fundamentals of poultry nutrition is critical to converting food into poultry eggs and meat efficiently and economically (Scanes & Christensen, 2020). Many books reported that nutrients required by poultry are classified into several categories, energy, carbohydrates, lipids (fats), protein and AAs, and minerals and vitamins (Blair, 2008; NRC, 1994; Scanes & Christensen, 2020). Each of these categories has specific functions that meet the nutritional requirements of the poultry.

2.2.1 Energy

One crucial element of poultry nutrition is the energy content in diet formulation since it can impact the animal's body and health. A variety of studies stated that energy is produced when the feed is digested in the animal's gut (Blair, 2008; Scanes & Christensen, 2020). Chickens need energy to grow body tissues, produce eggs, carry out physical activities, and maintain normal body temperature and functions (Scott et al., 1982). Energy is derived from the oxidation of carbohydrates, fats, and proteins in the feed (Blair, 2008; Scanes & Christensen, 2020). Common ingredients rich in energy include maize, wheat, RB, and cassava root (Cheeke, 2005). Scanes and Christensen (2020) reported that several factors can affect the metabolic rate of poultry, which is an indication of the energy needs of poultry. The factors include body size, breed, variety, strain, line, activities, period of darkness, environmental temperature, diet, level of production, feather coverage, and other factors like stress and disease that can impact dietary energy requirements (Scanes & Christensen, 2020).

Certain terms are used to describe connections in relation to dietary energy in the poultry industry. The energy value of feedstuffs is addressed in calories (Scanes & Christensen, 2020). A kilocalorie (kcal) equals 1,000 calories (cal)- this is a standard unit used to address energy in the poultry industry (NRC, 1994). A mega calorie (Mcal) equals 1,000,000 cal- this is also commonly used to express other nutrient requirements related to dietary energy (NRC, 1994). Energy units used in many countries across the world are based on joules (J), a kilojoule (kJ) equals 1,000 J, or a megajoule (MJ) equal 1,000,000 J (NRC, 1994). Similarly, a conversion factor to convert calories to joules, such as 1 Mcal equals 4.184 MJ, 1 MJ equals 0.239 Mcal, and 1 MJ equals 239 kcal (Blair, 2008). Thus, some tables display values in this study as MJ, kJ, and kcal/kg.

The following terms are used to address the dietary energy value. An instrument in a laboratory called the bomb calorimeter is used to burn feedstuff in the presence of oxygen under controlled conditions and measure the energy released in the form of heat (Blair, 2008; Scanes & Christensen, 2020). The value determined in this analysis is known as the total energy or gross energy (GE) (Blair, 2008; Scanes & Christensen, 2020). Gross energy is indicated as the heat of combustion (NRC, 1994). Scanes and Christensen (2020) determined that through a series of digestive and metabolic processes, the energy in feed is lost in the digestive system of poultry. Digestible energy (DE) is the portion of GE in the feed consumed less the GE of the feed excreted in the faeces (Blair, 2008; NRC, 1994; Scanes & Christensen, 2020). Metabolisable energy (ME) is the portion of GE consumed less the GE contained in the urine, faeces, and gaseous products of digestion (NRC, 1994). Blair (2008) stated that a more refined energy assessment of ME value corrected to zero protein nitrogen (N) retained or loss is named ME_n . Blair (2008) further described that the methods yield ME called apparent metabolisable energy nitrogen-corrected (AMEn), as all the energy lost in excreta derives from endogenous urinary secretions, sloughed-off intestinal cells, and endogenous secretions of digestive fluids. The GE of the feed consumed minus the GE of the feed origin's excreta is known as true metabolisable energy (TME) (Blair, 2008; Scanes & Christensen, 2020). Net energy (NE) is the ME minus the energy lost at the heat increment for productive and maintenance purposes (NRC, 1994; Scanes & Christensen, 2020).

2.2.2 Carbohydrates

Dietary carbohydrates are crucial elements in diet formulation. Carbohydrates act as a significant source of energy for poultry (NRC, 1994). Carbohydrates are derived from cereal grains like corn, grain sorghum, wheat, and barley and legumes like soybeans (NRC, 1994; Scanes & Christensen, 2020). Most cereal carbohydrates occur as starch, which birds readily digest (NRC, 1994). Certain carbohydrates including polysaccharides, such as pentosans, hemicellulose, and cellulose, and oligosaccharides, such as raffinose and stachyose, are poorly digested in birds (NRC, 1994). These carbohydrates include polysaccharides, such as pentosans, hemicellulose, and cellulose, and oligosaccharides, such as raffinose and stachyose, which birds poorly digest (NRC, 1994; Scanes & Christensen, 2020). Accordingly, these carbohydrates contribute little to meeting the energy requirements of poultry, and some even incur negative effects in the digestive processes of poultry when present in certain concentrations (NRC, 1994). However, Scanes and Christensen (2020) wrote that carbohydrates, predominantly glucose, are the primary energy sources in feeds, providing energy for all poultry activities if digested. Glucose is the primary source of fuel for the energy needed for poultry in body processes (Scanes & Christensen, 2020). Therefore, even though mostly carbohydrates are easily digested, if present in sufficient concentrations, they provide adequate energy in the diet.

2.2.3 Protein and Amino Acids

Proteins are critical components in all living organisms. Extensive research showed that protein is usually referred to as crude protein (CP), measured by finding the nitrogen (N) content and multiplying that by 6.25 (Cheeke, 2005; Scanes & Christensen, 2020). The average nitrogen content of protein is around 16% ($100/16 = 6.25$ g of protein) (Cheeke, 2005; Scanes & Christensen, 2020). Proteins are complex organic compounds derived from specific sequences of AAs (Scanes & Christensen, 2020). Common sources of protein in poultry nutrition are SBM, MBM, FM, CM, and insect meal (black soldier fly larvae) (Cheeke, 2005). Similarly, CLM can also be incorporated into the diet as an alternative source of protein (Bakare et al., 2020; Diarra & Devi, 2015; Ravindran, 1992). Although several studies stated that there are 22 different AAs (Blair, 2008; NRC, 1994); nevertheless, these studies agree to distinguish AAs into essential amino acids (EAAs) and nonessential amino acids (NEAAs)

(Cheeke, 2005; Scanes & Christensen, 2020). These studies define EAAs as AAs that poultry cannot synthesise at all or rapidly enough to meet metabolic requirements, which makes them essential to be supplied in the diet (Blair, 2008; NRC, 1994). On the other hand, the NEAAs, referred to as AAs, can be synthesised by poultry, which makes them nonessential to the diet (Blair, 2008; Cheeke, 2005).

Proteins and AAs in the diet are essential for animal growth. According to the NRC (1994), poultry uses AAs obtained from dietary protein to fulfil many functions. For instance, AAs, as proteins are primary constituents of protective and structural tissues, such as ligaments, bone matrix, feathers, skin, and soft tissues, including muscles and organs (NRC, 1994). Previous studies have shown that protein and AA requirements vary according to age and the state of the animal's development (Blair, 2008; Scanes & Christensen, 2020). NRC (1994) provided examples, such as broiler chicken, which has high AA requirements to meet the need for rapid growth. Similarly, the laying hen has higher AA requirements than the mature rooster, even though the mature rooster has a bigger body size, and its feed consumption is similar (NRC, 1994).

2.2.4 Lipids

Lipids or fats are helpful energy sources in poultry diets. Scanes and Christensen (2020) reported that fats supply energy in poultry diets, improve the dispersion of micro-ingredients in feed mixture and the physical consistency of feeds, and carry fat-soluble vitamins. Fats in poultry diets are derived from acidulated soap stocks from the vegetable oil industry, restaurant greases, poultry or animal fats obtained from the rendering industry, and the mixtures thereof (NRC, 1994; Scanes & Christensen, 2020), including palm oil (Leeson & Summers, 2005; Long et al., 2019; Saminathan et al., 2020). The nutritional value of fats can come from free fatty acids, unsaponifiable lipids, impurities, moisture, fatty acids, and total fatty acid composition (Scanes & Christensen, 2020).

Supplementing diets with fats can improve energy utilisation in chickens (Scanes & Christensen, 2020). NRC (1994) reported that adding fats to feed to complement carbohydrates leads to enhanced productive energy at the ME_n level. The impact of fat inclusion can increase body weight; however, after 20 weeks, the impact of fat on body weight progressively dissipates (NRC, 1994). Nonetheless, the impact of fats on feed efficiency

remains (NRC, 1994). Scott et al. (1982) showed that the benefits of providing fats in diets can only be obtained when the amounts of all other nutrients have met their proportion in the energy level. Scott et al. (1982) mentioned that including fats in diets can improve the efficiency of energy utilisation compared to those fed low-fat diets. All feed fats should be stabilised by an antioxidant to preserve unsaturated fatty acids and regularly monitored for possible undesirable residues such as chlorinated hydrocarbons, insoluble and unsaponifiable and peroxides (NRC, 1994).

2.2.5 Minerals and Vitamins

Minerals are inorganic elements essential for animal health. Many studies divide them into two categories, macro-minerals or macro-elements, which are required in relatively large amounts in the diet, while micro-minerals or micro-elements are required in small or trace amounts (Blair, 2008; Scanes & Christensen, 2020). Some ingredients in this research naturally contain minerals needed for poultry, limestone is mainly used as a source of calcium, DCP and TCP are used for calcium and phosphorus and some minerals (Leeson & Summers, 2005).

Macro-minerals are generally used as components of tissue structures like bone, while micro-minerals are used as cofactors or activators of enzymes (Cheeke, 2005). Macro-minerals include calcium (Ca), phosphorus (P), sodium (Na), potassium (K), chloride (Cl), magnesium (Mg), and sulphur (S) (Blair, 2008; Cheeke, 2005; Hynd, 2019). Meanwhile, some essential micro-minerals for poultry are copper (Cu), iodine (I), iron (Fe), manganese (Mn), selenium (Se), and zinc (Zn) (Blair, 2008; NRC, 1994; Scanes & Christensen, 2020). Other micro-minerals include chromium (Cr), molybdenum (Mo), and cobalt (Co) (Cheeke, 2005; Hynd, 2019; NRC, 1994). Meanwhile, NaCl and sodium carbonate are used to fulfil the sodium, chloride and other minerals intake for poultry (Khan et al., 1999). The requirements of micro-minerals often depend on the concentration present in feed ingredients; therefore, poultry may require supplementation to ensure adequate intake of micro-minerals (NRC, 1994).

Vitamins are required in poultry diets. Previous studies defined vitamins as an organic compound that is a component of natural food but is distinct from the other organic nutrients such as carbohydrates, lipids, protein, and water; it is required in minute quantities in the diet; it is essential for normal metabolism; when absent from the diet or not present in adequate quantity, specific deficiency symptoms develop; and animals cannot synthesise it, and thus it

is essential in the diet (Blair, 2008; Cheeke, 2005). Many of the ingredients included in this research have a diverse vitamin supply. Nonetheless, there are exceptions to the last characteristics of a vitamin. Vitamin D can be synthesised in the skin by animals exposed to sunlight, and B3 (niacin/nicotinic acid) is synthesised to some extent from AA tryptophan (Blair, 2008; Cheeke, 2005). The existing literature reported that vitamin C can also be synthesised by poultry; therefore, it is not considered in poultry's dietary requirements (Cheeke, 2005; Scanes & Christensen, 2020). However, there is some evidence of a favourable response to vitamin C by birds under stress (NRC, 1994; Scanes & Christensen, 2020).

It has been widely reported that vitamins are classified into two groups: fat-soluble vitamins and water-soluble vitamins (Hynd, 2019; Scanes & Christensen, 2020). Cheeke (2005) stated that fat-soluble vitamins are stored in fatty tissues of the animal body and are not excreted in the urine. The fat-soluble vitamins are vitamins A, D, E, and K (Hynd, 2019; Scanes & Christensen, 2020). The fat-soluble vitamins are absorbed in the dietary fats (Scott et al., 1982). In contrast, water-soluble vitamins, except for vitamin B12 (cyanocobalamin), are not stored and are readily excreted in the urine (Cheeke, 2005; Scott et al., 1982). If water-soluble vitamins are not in the diet, it can lead to deficiencies (Cheeke, 2005; Scott et al., 1982). The water-soluble vitamins are vitamin B1 (thiamine), B2 (riboflavin), B3, B5 (pantothenic acid), B6 (pyridoxine), B7 (biotin), B9 (folacin/folic acid), B12, choline, and vitamin C (Cheeke, 2005; Scanes & Christensen, 2020). Apart from vitamin C, water-soluble vitamins can be referred to as B-complex vitamins (Cheeke, 2005). Unlike protein and energy, animals are required to consume vitamins in extremely definite amounts per day, specifically in milligrams or other units per kilogram of diet (Scott et al., 1982).

2.2.6 Water

The literature consistently regarded water as an essential nutrient (NRC, 1994; Scanes & Christensen, 2020). Scanes and Christensen (2020) highlight that the amount of water required for poultry differs considerably. Water should be available *ad libitum*. These studies stated that birds drink twice as much water by weight as the feed they consume (Cheeke, 2005; Scanes & Christensen, 2020). Poultry drinking water varies based on body weight, age, production, diet, weather, environmental temperatures and humidity (Scanes & Christensen, 2020). This aligns with the statement that birds are sensitive to the temperature of the

drinking water, and they prefer cold water over ambient temperature, which can influence feed intake (Blair, 2008). Hence, poultry need to have free access to clean, fresh, and quality water according to their environment.

2.3 Selected Feed Ingredients

Many ingredients have been studied for their potential use in chicken diet formulation. Some ingredients are locally produced and available in their natural forms in WP, sourced from other islands in Indonesia, and imported from other countries. These ingredients provide nutrients needed for poultry nutrition.

2.3.1 Maize

Maize or corn (*Zea mays*) is the primary energy source in many poultry diets. Corn is the main cereal around the world due to its agronomic features and nutritional value in the poultry industry (Cheeke, 2005). Maize is adapted to a wide range of environmental and climate conditions, making this ingredient desirable to cultivate in diverse areas (Cheeke, 2005). Several authors have stated that maize can provide nutrients, including readily digestible carbohydrates (sugars and starch), oils and protein (Leeson & Summers, 2005; Scanes & Christensen, 2020). Cheeke (2005) indicates that corn is low in fibre, which accounts in part for its high digestible energy content for poultry. These nutrients are needed for poultry for egg production, growth, and maintenance (Scanes & Christensen, 2020).

2.3.2 Wheat

Wheat (*Triticum aestivum*) is a cereal grain which is widely used for poultry diets. Wheat is primarily for human consumption; it can be used as a livestock feed ingredient (Cheeke, 2005). While Leeson and Summers (2005) stated that wheat is much higher in protein content and lower in energy than corn; wheat contains fibre, carbohydrates, and fat, making this ingredient ideal for chicken diet formulation. Using whole wheat in the diet improves pellet durability and stimulates gastric motility and the gizzard while enhancing activity within an acidic environment, which is thought to reduce oocyte viability (Leeson & Summers, 2005). Nevertheless, Scanes and Christensen (2020) argue that wheat with enzyme supplementation can substitute for corn.

2.3.3 Rice Bran

Another ingredient that provides decent nutrition for the poultry diet is rice bran (RB) (*Oryza sativa*). Rice bran is a major by-product in tropical regions such as Indonesia and Thailand (Cheeke, 2005). Previous studies showed that rice bran is an ingredient valued as an energy source since it has a high oil content, which increases its energy value in diet formulation (Cheeke, 2005; Leeson & Summers, 2005; Sugiharto et al., 2018). Rice bran oil contents are slightly different in different studies, such as 13% (Cheeke, 2005) and 6-10% (Leeson & Summers, 2001, 2005). However, Cheeke (2005) stated that RB is a source of protein, AAs, and B vitamins. Sugiharto et al. (2018) added that RB contains not only nutrients but also prebiotics and other phytochemicals/nutraceutical compounds which can improve the host animal's health status. Nevertheless, its high content of enzyme inhibitor (trypsin inhibitor), phytate, and fibre may limit the utilisation of this ingredient in poultry diets unless further fermentation is employed to improve the functionality of rice bran for poultry diets (Sugiharto et al., 2018). Heat treatment may stabilise RB, which can improve its use in poultry diets by inactivating trypsin inhibitors and lip-oxidases (Cheeke, 2005). Extrusion at 130°C significantly decreases the chances of rancidity and the development of free fatty acids (Leeson & Summers, 2001, 2005). With the nutrient contents in RB, this ingredient can be incorporated into the chicken diet.

2.3.4 Cassava Root Meal

Cassava, tapioca, or manioc (*Manihot esculenta*) has the potential to offer nutrients to poultry. Many studies show that cassava is a carbohydrate source that provides high energy and starch but low fat and protein content (Ogbuewu & Mbajorgu, 2023; Sugiharto et al., 2018). Ravindran (2013) and Cheeke (2005) reported that cassava is high in starch and fibre, an excellent energy source, and can replace maize in poultry diets. When formulating the diet, cassava needs to be further processed, such as cassava meal (Ogbuewu & Mbajorgu, 2023). Cassava root meal (CRM) comes from cassava root that has been peeled and dried, then processed into powder (Ogbuewu & Mbajorgu, 2023). Besides Indonesia, the practice of using cassava as a chicken diet ingredient has been implemented in Thailand (Khempaka et al., 2022) and Papua New Guinea (Glatz, 2017). These studies found that utilising cassava root with further fermentation to process cassava removes its anti-factors, like cyanogenic

glucosides (Cheeke, 2005; Glatz, 2017; Ogbuewu & Mbajorgu, 2023). Previous research shown that cassava would improve egg production and quality when it is in an appropriate amount (Khempaka et al., 2022; Ogbuewu & Mbajorgu, 2023). Therefore, cassava has been shown to be used in the chicken diet.

2.3.5 Soybean Meal

Soybean meal (SBM) is a crucial ingredient in completed poultry diets. Cheeke (2005) wrote that SBM comes from soybeans (*Glycine max*) that are originally from China. Soybean usage has grown rapidly in the poultry industry in the United States of America (USA) since 1950 (Cheeke, 2005). Nowadays, SBM has become a significant protein source in many parts of the world with intensive animal and poultry production (Cheeke, 2005) due to the efficient production of the plant source and its high protein content (Scanes & Christensen, 2020). The findings from Tangendjaja (2020) show that SBM is a source of rich protein ingredients that are used for animal development and growth. Leeson and Summers (2005) detail that SBM offer high protein content and AAs, including methionine, lysine, arginine, tryptophan and threonine. This resonates with the studies from Cheeke (2005) that stated that SBM has high digestibility, protein, and AAs, is highly palatable, and is suitable for a balanced corn-soy diet for swine and poultry production when further supplemented with vitamin B12. Pond et al. (2005) stated that SBM is also a source of energy; nevertheless, this ingredient is mainly incorporated in diet formulation as a plant protein source. Soybeans can be given to livestock after appropriate heat treatment (100°C for 3 min) to inactivate trypsin inhibitors (Cheeke, 2005; Pond et al., 2005). The product of this treatment is referred to as full-fat SBM, which contains approximately 38% CP, 18% fat, and 5% CF (Crude Fibre) (Pond et al., 2005). The heat treatment of SBM necessitates striking a balance between not overheating to cause damage to the protein and adequate heating to inactivate toxins (Cheeke, 2005). This heated meal has favour in diets for swine and poultry (Pond et al., 2005; Scanes & Christensen, 2020).

2.3.6 Meat and Bone Meal

Meat and bone meal (MBM) is a by-product of animals that contains the nutrients needed for a poultry diet. Leeson and Summers (2001) refer to MBM as animal by-products with bone that contains around 8% calcium, 4% phosphorus and protein levels of approximately 50% on a dry matter (DM) basis. A slight difference between Leeson and Summers (2001), Cheeke

(2005) found that MBM contains 7-10% calcium and 3.8-5% phosphorus. MBM usually has around 12% fat, and the best quality MBM will be stabilised with antioxidants such as ethoxyquin (Leeson & Summers, 2001). Many studies portray MBM as high in protein and minerals (calcium and phosphorus), fat, and EAAs (Leeson & Summers, 2005; Yanuartono et al., 2020). Cheeke (2005) stated that MBM has lower protein quality and is less palatable than SBM. The percentage of minerals also depends on the meat and bone proportions in the product (Cheeke, 2005).

In addition, a recent concern with MBM is microbial content, specifically *Salmonella* contamination (Cheeke, 2005; Leeson & Summers, 2001). Major problems in the United Kingdom (UK) are due to improperly processed renderers' products with salmonella-infected poultry by-products, leading to widespread salmonella contamination of broilers and eggs when the feed contained the infected MBM (Cheeke, 2005). Cheeke (2005) highlighted that MBM and other animal by-products must be properly heat-sterilised during processing to avoid further contamination. The quality of MBM depends on the dilution of tendinous tissue and bone, the temperature of the tissue, and the methods used in processing (Pond et al., 2005). The proper methods for processing MBM can reduce the contamination content in MBM.

2.3.7 Fish Meal

Fish meal (FM) is a by-product of the fishery industry that provides nutritional ingredients to poultry. Scanes and Christensen (2020) mentioned that the nutritive value of FM depends on the amount of oxidation, the method of drying and the types of fish, including white fish, salmon, herring, sardine, and menhaden. According to previous studies, FM is a source of protein and EAAs (Leeson & Summers, 2005; Pond et al., 2005). Scanes and Christensen (2020) stated that fish meals have 57% to 77 % protein content, while Leeson and Summers (2005) found that the CP in fish meals is about 60%. However, if FM is not properly stored and processed, the digestibility of protein declines considerably (Scanes & Christensen, 2020). Scott et al. (1982) clarified that FM is a good source of EAAs like methionine and lysine. The AAs are crucial for livestock's overall health and growth (Leeson & Summers, 2005). Cheeke (2005) and Pond et al. (2005) agreed that fish meals provide various minerals, including phosphorus, calcium, micro-minerals and vitamins. FM is highly palatable to poultry and swine

and is generally utilised in starter diets for chickens, turkeys, and swine due to their high protein and AA content (Cheeke, 2005). Common FM around the world includes herring meals from the USA, Iceland, Norway, and Canada; anchovy meals from Ecuador (Peruvian fish meal), Chile, and Peru; pilchard meals from South Africa; and menhaden meals from the Atlantic coasts and the Gulf of the USA (Cheeke, 2005).

2.3.8 Copra Meal

An alternative feedstuff used in poultry diets is copra or coconut meal (CM). Scott et al. (1982) and Sugiharto et al. (2018) highlight that CM is one source of proteins and energy utilised to balance AAs in poultry diet, derived from the coconut tree (*Cocos nucifera*). Both Pond et al. (2005) and Cheeke (2005) indicated that the CP is low, from 20-26%, and of variable digestibility. The methionine content is higher than for SBM, but the lysine content is lower (Cheeke, 2005). Copra meal has become a popular protein supplement for livestock in tropical regions (Cheeke, 2005). A study on the fermentation of copra meal with *Trichoderma* spp. in broiler diets with 30% copra content can provide a balanced diet, particularly in terms of energy and amino acids (AAs), which leads to improved broiler performance (Sugiharto et al., 2018). Meanwhile, in Palu, Indonesia, fermented copra dregs with 4% ammonium sulphate can improve layers' haugh unit (HU) and slight dry excreta; the study did not mention the effects of copra meals (Adjis et al., 2021). The HU is a measurement used to correlate egg weight with albumen (egg white) height to identify the freshness and quality of eggs (Junior et al., 2024). According to Junior et al. (2024), the United States Department of Agriculture (USDA) divided the HU of eggs into excellent as > 73 HU; good quality as 60-72 HU; medium quality as 55-30 HU; and low quality as < 30 HU. Nonetheless, the study by Adjis et al. (2021) suggests that coconut by-products have the potential to improve poultry performance when properly fermented and included in the ration.

2.3.9 Black Soldier Fly Larvae

Black soldier fly larvae (BSFL), with the scientific name of *Hermetia illucens*, contain many nutrients needed in chicken diet formulation. The BSFL is high in crude fat, crude protein, amino acids, vitamins, and minerals (El-Hack et al., 2020; Putra et al., 2023). The BSFL contain 42% CP and 35% ether extract (Cheeke, 2005). In Ravindran's study, it was stated that BSFL can replace fishmeal in the formulation (Ravindran, 2013). In another study in Malaysia, BSFL

in the diet has been shown not to affect egg quality and has no adverse health effects on laying chickens (Zaid et al., 2023). Moreover, both Putra et al. (2023) and Zaid et al. (2023) have demonstrated that BSFL can improve gut health and reduce the levels of pathogenic bacteria, which can improve overall immune chicken response. Furthermore, El-Hack et al. (2020) suggested that the utilisation of BSF grown on household and farm wastes in poultry feed manufacturing can impact the decline of organic waste within. Considering the nutrient contents and the benefits reinforces the potential of using BSFL as an animal feedstuff.

2.3.10 Cassava Leaf Meal

Cassava leaf meal (CLM) comes from cassava or tapioca leaves (*Manihot esculenta*), which have a nutritional composition that can be used in chicken diets. Glatz (2017) stated that cassava leaves are a good source of protein, containing around 20% protein. Ravindran (1992) stated that cassava leaves are rich in minerals and vitamins, including Ca, Fe, Mg, Mn, Zn, riboflavin, vitamin A and ascorbic acid, beneficial for poultry. Diarra and Devi (2015) reported that the CP content of cassava leaves was from 16.7-39.9%. Cassava leaves are good source of xanthophylls and vitamins, a substance that improves the egg yolk and egg skin (Diarra & Devi, 2015). Supporting this, many studies have shown the utilisation of CLM in chicken diets for broilers and layers (Diarra & Devi, 2015; Glatz, 2017). Hadjipanayiotou (1985) reported that CLM has some yellow pigments that give a good egg yolk pigmentation. Hadjipanayiotou (1985) further mentioned that up to 10% CLM will give no difference in egg weight, feed efficiency, and egg production. Cassava leaf meal, when portioned properly, can improve broilers' carcass quality and improve the HU on layers (Diarra & Devi, 2015; Glatz, 2017).

However, a plethora of studies have reported that cassava leaves have significant levels of the anti-nutrient hydrogen cyanide (HCN) (Bakare et al., 2020; Diarra & Devi, 2015; Ravindran, 1992). The high presence of HCN and high fibre content may limit the efficient utilisation of CLM for monogastric diets (Diarra & Devi, 2015; Ravindran, 1992). Diarra and Devi (2015) further explained that the HCN content of the leaves was influenced by the genetic, physiological, edaphic, and climatic factors. Accordingly, further processing of cassava leaves is needed to improve the bioavailability of nutrients for poultry (Bakare et al., 2020).

2.3.11 Palm Oil

An ingredient that can be utilised in the chicken diets is palm oil (PO) (*Elaeis guineensis*). Saminathan et al. (2020) reported that PO was derived from extracted fresh fruit bunches by a mechanical process. Palm oil has been used in poultry diet as a source of energy, and is rich in tocopherols, tocotrienols, and carotenoids with antioxidant properties, which all contribute to nutritional properties and stability of PO (Long et al., 2019). Using fats or oils in a diet can be beneficial for palatability and texture (Leeson & Summers, 2005). Since fats or lipids can contain twice the energy of proteins and carbohydrates per unit of weight, the inclusion of lipids from animal fats and vegetable oils is necessary to increase diet energy (Long et al., 2019). Adding lipids or oils to the diets can improve the growth of poultry under excessively high or low temperatures due to the effect of supplemental dietary fat (Long et al., 2019). The dietary fats improve absorption and utilisation efficiency of other nutrients and enhance the utilisation of metabolisable energy and protein (Long et al., 2019).

The use of PO in diets has enhanced the body weight gain (BWG) and improved feed conversion ratio (FCR) and meat quality, hence, positively impacting the production performance of broilers (Saminathan et al., 2022). Saminathan et al. (2022) reported that even though PO can enhance the survival rate of broilers in extreme high ambient temperature situations, it is suggested to consider analysing changes in different environments, including increased temperature. Saminathan et al. (2020) found that adding PO enhances egg quality by improving colour intensity and increasing the fatty acid content of egg yolk. However, utilising PO as a feed ingredient in the laying rations needs to be weighed properly to yield optimum egg production (Saminathan et al., 2020). The high level of antioxidants in PO and the high dietary inclusion level of lipids may lead to oxidative stress in animals; accordingly, the inclusion of palm oil in diets is limited to 4-6% (Long et al., 2019). The proper amount of PO in the diet can improve the growth performance and modulate the balance of nutrients in poultry.

2.3.12 Limestone, Dicalcium Phosphate, and Tricalcium Phosphate

In formulating chicken diets, ingredients that are sources of calcium and phosphorus must be integrated, including limestone, dicalcium phosphate (DCP), and tricalcium phosphate (TCP). Lee et al. (2022) and Lima et al. (1999) agree that phosphorus and calcium are crucial in overall

metabolic health and bone development; these minerals are essential for the maintenance and formation of the skeleton of animals (NRC, 1994). Phosphorus is important to muscle coordination, carbohydrate, energy, fat and AA metabolism, normal blood chemistry, nervous tissue metabolism, skeletal growth and transport of fatty acids and other lipids (Leeson & Summers, 2001). Calcium is important for blood clotting and for acid-base balance in the body (Leeson & Summers, 2001). Dietary phosphorus and calcium are required in the proper ratio to one another (Leeson & Summers, 2001).

Limestone is the main source of calcium that can impact dietary formulation. Leeson and Summers (2005) and NRC (1994) agree that limestone contains 38% calcium, while Cheeke (2005) reported it to be 36% calcium. Ground limestone is usually the best option to supply calcium in diets (Cheeke, 2005; Scanes & Christensen, 2020). Gilani et al. (2022) showed that limestone inclusion in the chicken diet is crucial for overall metabolic functions, eggshell quality, and bone formation. These findings align with Leeson & Summers (2001) and NRC (1994) that for laying hens, the major portion of calcium in the feed is used for eggshell synthesis, while in the growing chicken, the major portion is used for bone formation.

Equally, DCP and TCP can be included in chicken diets. Dicalcium phosphate contains around 18.5% phosphorus and 18-24% calcium (Toama, 2017), or 18-21% phosphorus and 25-28% calcium (Cheeke, 2005). While based on Leeson and Summers (2005), DCP contains 21% calcium and 20% phosphorus. Similarly, in their research, Lima et al. (1999) showed that TCP is a primary source of phosphorus and calcium. Toama (2017) demonstrated that a mixture of phosphate rock, phosphoric acid, sodium hydroxide, and calcining at high temperatures generates TCP. Tricalcium phosphate comprises around 18% phosphorus and 30% calcium (Toama, 2017), but according to Leeson and Summers (2005), TCP contains 23% calcium and 19% phosphorus. DCP, TCP and Limestone are necessary in the diets due to their beneficial components of calcium and phosphorus in the diets. Therefore, the inclusion of DCP, TCP and/or limestone as sources of phosphorus and calcium is needed in the diet to enhance poultry performance.

2.3.13 Lysine, DL-Methionine, and L-Threonine

Lysine, DL-methionine, and L-threonine are ingredients used in poultry diets. Lysine, DL-methionine, and L-threonine are synthetic AAs derived from bacterial fermentation, a new technique in biotechnology used to increase the amount of AAs available while reducing the cost (Cheeke, 2005). The use of synthetic AAs is because to an economic decision in most situations, and so their prices tend to shadow that of SBM, which is the major source of protein (Leeson & Summers, 2001, 2005). Cheeke (2005) stated that the main purpose of protein supplements in poultry diets is to supply the EAAs, as the grain portion is deficient in protein. Scanes & Christensen (2020) added that these AAs are purified and added to poultry diets to meet the specific needs of the EAAs requirements. Multiple studies have reported that these AAs are critical for protein synthesis and are usually added to balance the AAs level in livestock feed (Ojano-Dirain & Waldroup, 2002; Tenesa et al., 2016). Lysine can improve overall health and muscle development (Si et al., 2004; Tenesa et al., 2016). Methionine can maximise poultry growth and metabolism (Si et al., 2004). L-threonine can improve feed efficiency and enhance the production of antibodies and collagen (Ojano-Dirain & Waldroup, 2002; Tenesa et al., 2016). The application of lysine, DL-methionine, and L-threonine is broadly necessary for livestock feed.

2.3.14 Sodium Chloride and Sodium Carbonate

Sodium chloride or salt (NaCl) can be used in feed diets. Most diets use salt in the form of sodium chloride (Leeson & Summers, 2005). According to Cheeke (2005), the addition of 0.25 to 0.5% salt is a standard portion in poultry diets. FAO, 2013 stated that common salt can be included at levels of 0.2 to 0.4 percent. Watkins et al. (2005) show that sodium chloride is a source of sodium and chloride content in feed diets. High levels of sodium chloride can result in increased water intake (Leeson & Summers, 2005). Nonetheless, the proper balance of sodium chloride can help maintain health and feed efficiency and maximise growth (Watkins et al., 2005). Similarly, sodium carbonate (Na_2CO_3) can be utilised in diet formulation. Khan et al. (1999) demonstrated that sodium carbonate balances pH levels, making this ingredient important in diet formulation. Both sodium chloride and sodium carbonate are used in small portions of the diet, but they are important to the poultry.

2.3.15 Mineral and Vitamin Premixes

Mineral and vitamin premixes are significant in the dietary formulation. In their book, Leeson and Summers (2005) wrote that some natural ingredients have gradually been replaced and supplemented with extremely small quantities of purified and synthetic ingredients, including minerals, pigments, vitamins, and various pharmacological compounds. Subsequently, mineral and vitamin deficiencies may result in a lack of protection against chemicals, disease, and drug toxicity (Leeson & Summers, 2005). Previous research shows that these premixes ensure nutritional balance in animal diets (Asaduzzaman et al., 2005; Ribeiro et al., 2021). In broiler diets, Ribeiro et al. (2021) documented that mineral and vitamin premixes optimise performance improvement and bone quality. Meanwhile, for layer diets, Asaduzzaman et al. (2005) reported that these premixes can improve egg production, enhance growth, and provide health benefits. These premixes are needed to meet the nutritional balance shortages for poultry (Asaduzzaman et al., 2005; Ribeiro et al., 2021).

2.4 Ration Formulation

According to Dryden (2008), ration formulation is a mathematical technique for creating a mixture of feed ingredients in certain amounts that will provide adequate amounts of nutrients for animals. Dryden (2008) provided arguments that ration formulation allows for preparing a required nutrient concentration at the least cost or optimal in some other way, like maximising profits or minimising pollution. Ration formulation allows the planning strategy of purchasing ingredients based on price data, which may be excluded from the formulation, imposing constraints on ingredients used, including requiring the formulation to contain specific ingredients at certain levels or preventing the use of particular ingredients at less than or greater than a specified level (Dryden, 2008). The need to undertake ration formulation can improve efficiency and economic benefits while meeting the nutrient requirements adequately.

Dryden (2008) also stated that ration formulations allow the setup of ration nutrients used with upper or lower limits on the concentration of a nutrient, optimising ingredient allocation across a variety of rations. Based on Dryden (2008), ration formulation can allow the utilisation of a sub-programme to calculate nutrient requirements for the animal. Typically, increasing AA density will enhance productivity but lead to a more expensive feed, but it depends on the

ratio of the ingredients (Alhotan, 2021). Profitability will depend on income from saleable products and feed costs (Alhotan, 2021). Energy and protein requirements change according to the age of animals (Leeson & Summers, 2001, 2005). Limiting the concentration of a nutrient depends on the different stages of poultry, since each stage requires different nutrients for their metabolism, growth, and productivity (Dryden, 2008). Accordingly, when formulating a ration, updated information on energy and protein requirements needs to be considered according to age.

The main goal of feed mills is to produce nutritional and safe feed products at the lowest possible cost to optimise profits (Irawan et al., 2022). Cheeke (2005) stated that the objectives of feed formulation are to formulate diets to meet the nutrient requirements of animals and provide the optimum economic return to livestock producers. Thus, feed formulation is vital in the feed industry (Irawan et al., 2022). Animal feed rations need to be re-formulated because of changes in nutritional values, raw material prices, or production changes (Csikai, 2011). Each re-formulation must be recorded for traceability purposes (Csikai, 2011). Furthermore, Leeson and Summers (2005) mention that feed formulation needs to address diseases, environmental issues, feed toxins, bacteria, and contaminants that can influence its quality. Formulating animal diets focuses on achieving the lowest cost possible with the given constraints regarding animal requirements and nutritive values of ingredients.

2.5 Linear Programming

According to Hillier & Lieberman (2005), linear programming (LP) is a mathematical tool to describe the general problem of allocating limited resources among competing activities in the best possible way (optimal way). All objectives and constraints must be linear (Hillier & Lieberman, 2005). The word programming means involving planning (Hillier & Lieberman, 2005). Therefore, LP involves planning activities to obtain a maximum outcome that reaches the specified goal best according to the mathematical model among all the feasible alternative functions (Hillier & Lieberman, 2005; Vanderbei, 2020). In making the best choice between available alternatives, it is important to bring the objectives or intentions of the company to accomplish into the analysis (Buglear, 2012). Linear programming is designed to solve problems in which an optimal choice has to be made from the alternatives that the constraints collectively permit, the feasible solutions (Buglear, 2012). Even though allocating resource

activities is the most common application of LP, LP has various other important applications (Hillier & Lieberman, 2005). Any problem whose mathematical model suits the general format for an LP model is an LP problem (Hillier & Lieberman, 2005). A standard form of the mathematical model for the general problem of allocating resources to activities is shown in Figure 3.

	Maximise	$Z = c_1x_1 + c_2x_2 + \dots + c_nx_n,$	1
Subject to,			
		$a_{11}x_1 + a_{12}x_2 + \dots + a_{1n}x_n \leq b_1$	2
		$a_{21}x_1 + a_{22}x_2 + \dots + a_{2n}x_n \leq b_2$	3
		\vdots	\vdots
		$a_{m1}x_1 + a_{m2}x_2 + \dots + a_{mn}x_n \leq b_m,$	m
and			
		$x_1 \geq 0, \quad x_2 \geq 0, \quad \dots, \quad x_n \geq 0.$	
Note:			
		$Z =$ value of the overall measure of performance.	
		$x_j =$ level of activity j (for $j = 1, 2, \dots, n$).	
		$c_j =$ increase in Z that would result from each unit increase in level of activity j .	
		$b_i =$ amount of resource i that is available for allocation to activities (for $i = 1, 2, \dots, m$).	
		$a_{ij} =$ amount of resource i consumed by each unit of activity j .	

Figure 3. A Standard Form of the Model (Hillier & Lieberman, 2005).

In understanding the LP model, common LP terminologies need to be addressed. Hillier and Lieberman (2005) explain that the model poses the problem in terms of making decisions about the levels of the activities, so x_1, x_2, \dots, x_n are referred to as the decision variables. The values of $a_{ij}, b_i,$ and $c_j,$ (for $i = 1, 2, \dots, n$) are the constants of the model, and are called the parameters of the model (Hillier & Lieberman, 2005). The function being maximised Z is referred to as the objective function (Hillier & Lieberman, 2005), which is always to minimise or maximise some linear functions of these decision variables (Vanderbei, 2020). Equations 2 to m are referred to as constraints (Hillier & Lieberman, 2005). However, in LP, inequalities (\leq or \geq) are presented typically as constraints, while it is uncommon for goal programming to have an equality model ($=$). In addition, the $x_j \geq 0$ restrictions are known as the nonnegativity condition (Hillier & Lieberman, 2005).

Equally, other terminologies used in LP modelling are further mentioned. When a problem has only two decision variables and thus only two dimensions, a graphical procedure can be applied to solve it (Hillier & Lieberman, 2005). Hillier and Lieberman (2005) show that this procedure involves constructing a two-dimensional graph with x_1 and x_2 as the axes. The first step is to identify the values of (x_1, x_2) that are permitted by the constraints that are imposed by drawing each line that borders the range of permissible values for one constraint (Hillier & Lieberman, 2005). Any specification of values for the decision variables is known as a solution (Hillier & Lieberman, 2005; Vanderbei, 2020). Solutions are divided into different types. A feasible solution is a solution when all the constraints are satisfied (Vanderbei, 2020). An infeasible solution is one in which at least one constraint is violated (Vanderbei, 2020). The resulting region of permissible values of (x_1, x_2) is referred to as the feasible region (Hillier & Lieberman, 2005). The feasible region is the collection of all feasible solutions (Hillier & Lieberman, 2005). A range of possible outcomes in LP are illustrated graphically in Figures 4-9. Figure 4 depicts the feasible region. In Figure 5, feasible solutions are at the points $(2,3)$ and $(4,1)$ and infeasible solutions are at the points $(-1,3)$ and $(4,4)$. In this research, the constraints are nutrition specifications for poultry, minimum and maximum inclusion of nutrients, or zero inclusion for certain ingredients, and cost of feed ingredients. The goal is to find the least-cost diet possible while meeting the nutrient requirements and given constraints (Hreţcanu & Hreţcanu, 2010).

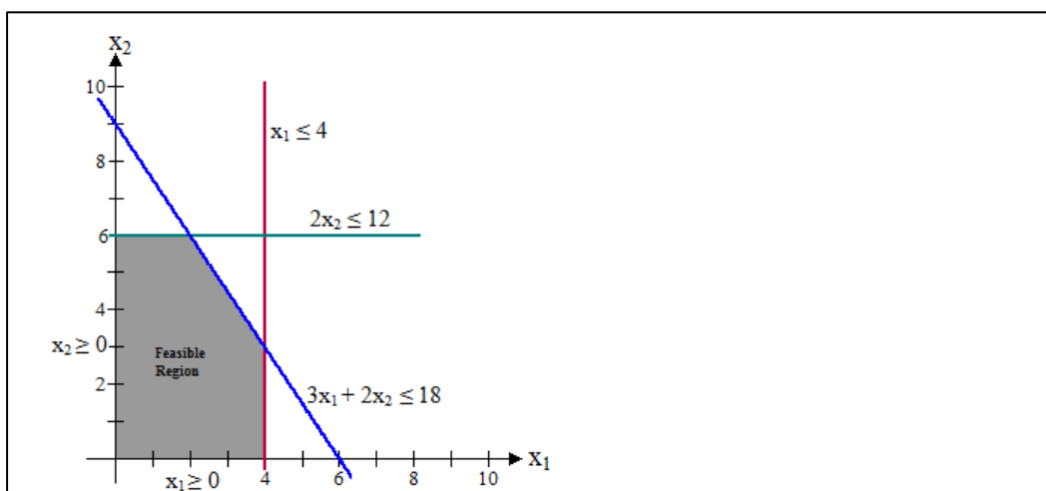


Figure 4. Feasible region (Agarwal, 2024).

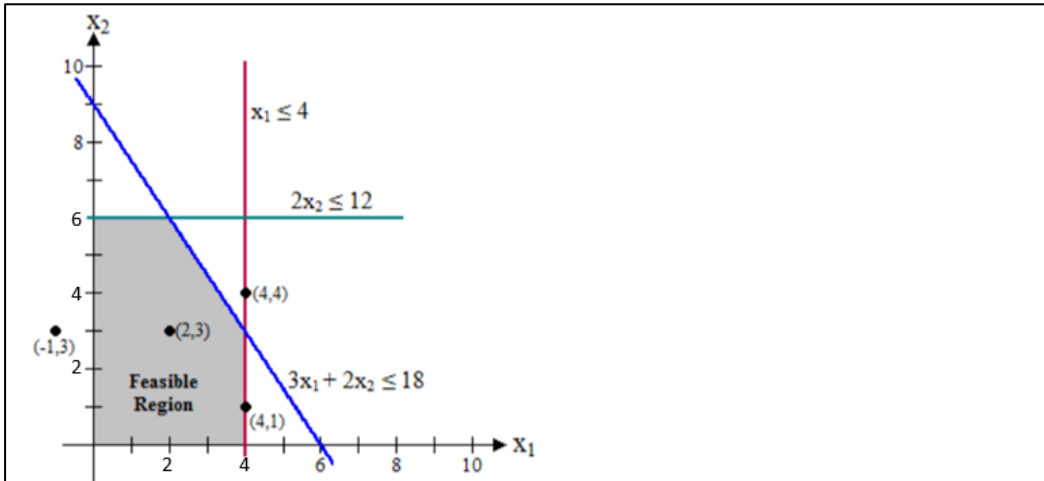


Figure 5. Feasible region, feasible solutions and infeasible solutions (Agarwal, 2024).

There could be multiple optimal solutions to a problem (Hillier & Lieberman, 2005). In Figure 6, the points (2,6) and (4,3) would be optimal. A feasible solution that has the most favourable value of the objective function is called the optimal solution (Hillier & Lieberman, 2005). If the objective function is to be maximised, the most favourable value is the largest value (Hillier & Lieberman, 2005). On the contrary, if the objective function is to be minimised, the most favourable (Hillier & Lieberman, 2005). Align with Hreţcanu & Hreţcanu (2010) that stating that the goal is when LP find and compare multiple feasible solutions, LP algorithms will stop until no better solution found. It is possible to have multiple optimal solution, even though most correctly specified problems will have just one optimal solution.

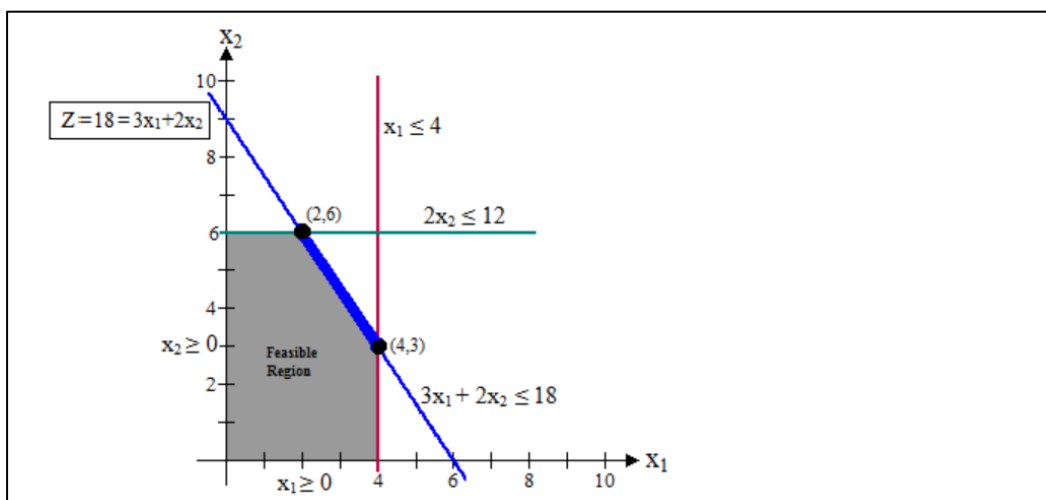


Figure 6. Multiple solutions (Agarwal, 2024).

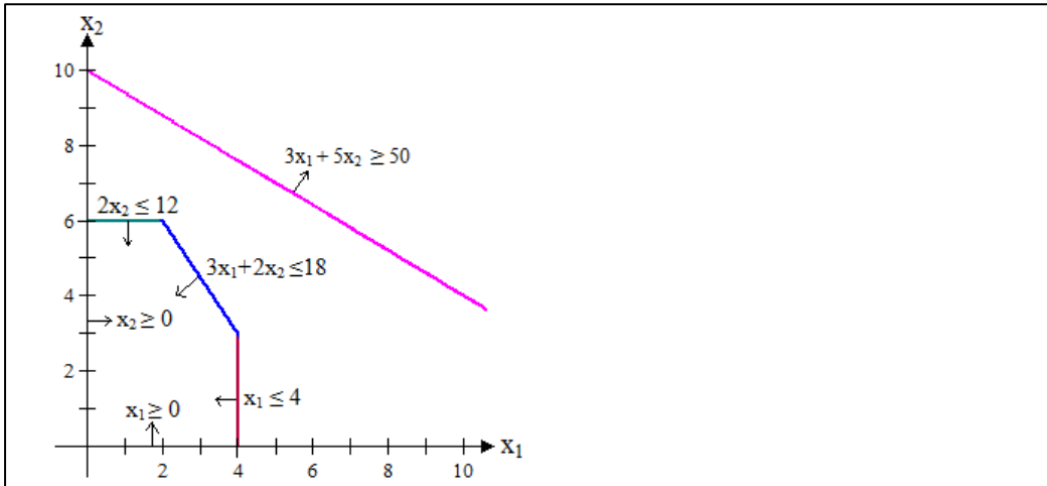


Figure 7. No Feasible solutions; therefore, no optimal solutions (Agarwal, 2024).

However, it is also possible to have no feasible solution (Hillier & Lieberman, 2005). Figure 7 shows that the LP problem has no feasible solutions; therefore, this LP problem has no optimal solutions. These are only possible if (1) there is no feasible solution, or (2) the constraints do not prevent the objective function (Z) value from continuously improving in a positive or negative direction (Hillier & Lieberman, 2005). In some other cases, there is an unbounded objective or an unbounded Z (Hillier & Lieberman, 2005). Figure 8 demonstrates that the solution of an LP problem is unbounded because the only constraint was $x_1 \leq 4$. After all, x_2 can then be infinitely increased in the feasible region without ever meeting the maximum value of $Z = 3x_1 + 5x_2$. In relation to diet formulations, this complied with Rambelosen et al. (2007) reporting in find infeasible solution due to the nutritional constraints on their dietary specifications. Understanding the probability of infeasibility in diet formulations is critical when the constraints like nutrient requirements, cost and inclusion level of ingredients, or unavailability of ingredients may influence the diet cost solution.

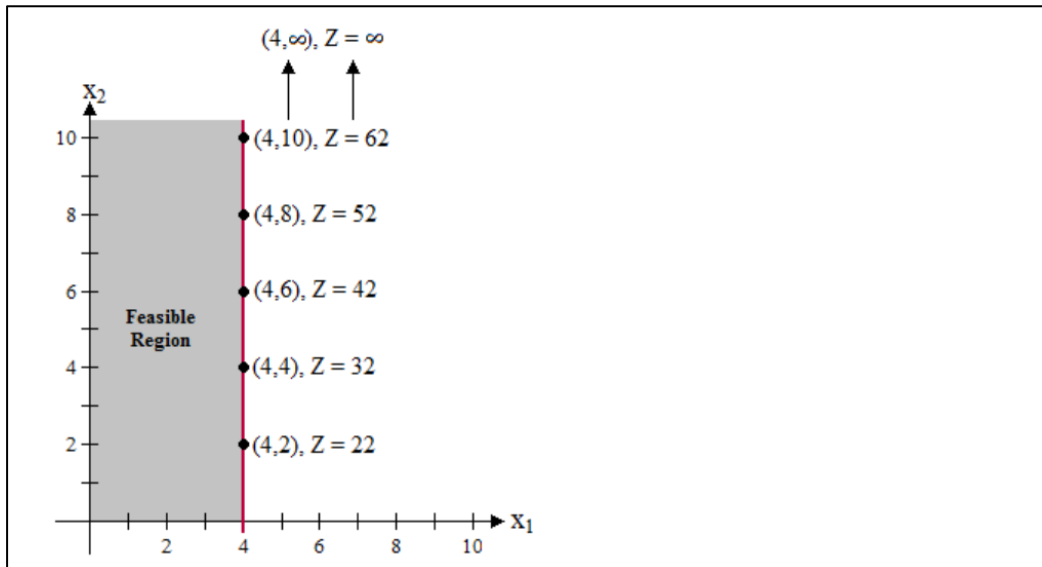


Figure 8. Unbounded solutions (Agarwal, 2024).

Lastly, a solution that lies at a corner of the feasible region is known as a corner-point feasible (CPF) solution (Hillier & Lieberman, 2005). All optimal LP solutions are corner solutions, within bounded feasible regions. If an LP problem has only one optimal solution, it must be a CPF solution (Hillier & Lieberman, 2005). If the problem has multiple optimal solutions, at least two must be CPF solutions (Hillier & Lieberman, 2005). However, if a CPF solution shows $(0,0)$, there could be a formulation problem; it depends on the objectives being solved, whether to maximise or minimise the values and the expected outcomes. In Figure 9, the five dots demonstrate the five CPF solutions. The last step is to choose the point in the feasible region that maximises or minimises the value of the objective function (Hillier & Lieberman, 2005). The objective function needed to be evaluated at each of the five CPF, then compare the values of the objective functions. After evaluating the values of the objective functions of each CPF, it is to choose the which values according to the problems. If the objective functions are for maximisation problems, select the maximum value; while, for minimisation problems, select the minimum values as the optimal solution (Hillier & Lieberman, 2005). In the graphical solution, this step can efficiently be done by trial and error to determine if there are any values of (x_1, x_2) in the permissible region that yield the optimal value (Hillier & Lieberman, 2005). These terminologies can be useful to understand when running the LP model.

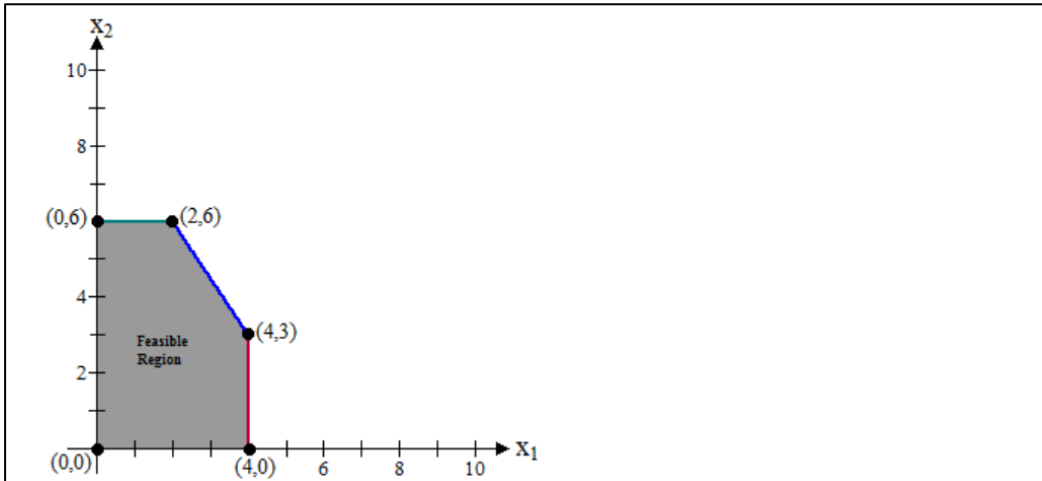


Figure 9. Five CPF solutions (Agarwal, 2024).

The utilisation of LP models has been implemented in poultry feed optimisation. The least-cost ration is a mixture of ingredients that meet the specified nutrient requirements, making the ratio of ingredients crucial (Dryden, 2008). Linear programming allows us to optimise only one objective (usually cost), but inputting constraints can help to shape a ratio that meets the other objectives (Dryden, 2008). However, adding additional constraints will increase the risk of being unable to formulate a feasible ration (Dryden, 2008). By addressing the least-cost ration, LP has been used to identify real-world problems (Dryden, 2008). An LP algorithm is a mathematical routine that calculates the quantities of ingredients that meet specified nutrient requirements (Dryden, 2008). In the least-cost LP, minimising cost is the only objective applied without violating any constraints (Heidari et al., 2021). Research incorporating the LP approach to optimise poultry feed production has been applied in a feed mill in Nigeria (Owolabi et al., 2015), research in Bogor, Indonesia (Irawan et al., 2022), and much literature has proved that LP is used to solve the diet formulation problems (Pond et al., 2005; Scanes & Christensen, 2020). In Bogor, Indonesia, Irawan et al. (2022) have researched optimising broiler feed production with low ingredient costs while meeting nutritional requirements by integrating LP. They have used LP to develop the diet formulation at the lowest cost while meeting the nutritional requirements (Irawan et al., 2022). These have shown that LP has had an enormous impact in recent decades.

2.6 Conclusion

Overall, this literature review on SCM, poultry nutrition, feed ingredients, ration formulation and LP provides a critical understanding of creating chicken diet formulation. The poultry nutrition and each ingredient discussed in this section provide valuable background information in formulating diets since each of the nutrients in the ingredients can influence the ration formulation. With the understanding of the supply chain of the ingredients and cost related to putting values in LP, this literature review can help in discussing whether formulating chicken diets in WP, Indonesia, is worth considering these nutritional, economic, and supply chain aspects.

2.7 Gaps in Literature

Even though extensive research in this area has provided the foundation, there is still a considerable gap. There is limited discussion of comparative studies of locally produced and imported ingredients in formulating chicken diets and their supply chain in WP, Indonesia. Furthermore, studies on utilising LP and ingredient nutrient composition and their effects on chicken productivity, egg and meat quality, and cost-effectiveness remain lacking in the region. In addition, the identified gap includes some areas such as nutritional comparison, economic analysis, environmental impacts, performance metrics, animal health and welfare, and sociocultural concerns in tropical regions. In optimising the production of poultry feed in WP, Indonesia, these research gaps can provide remarkable input to ensure economic, environmental, and business benefits while meeting the poultry nutrient requirements.

Chapter 3: Research Methods

This chapter will focus on describing the research methods in this study. This chapter consists of several sections. The first section details the aim and objectives of this research. The following sections exhibit the research design before providing the process of selecting the study area. After that section, this research will explain the data collection methods and data analysis. The subsequent part provides data privacy and ethical implications. Finally, this paper will present the study's validity and reliability.

3.1 Research Aim and Objectives

The research aims to investigate the supply chain of livestock feed ingredients by considering the cost, dependability, and availability of local and imported ingredients in MKW, WP, Indonesia. This research provides an approach incorporating LP and ingredient nutrient composition values in optimising diet formulation for their cost-effectiveness and nutritional content in broiler and layer chicken diets. The results are estimated to propose suggestions to enhance the efficiency of poultry production and sustainability in WP, Indonesia.

In accomplishing the aim of this research, the following objectives have been determined:

1. To investigate the supply chain for livestock feed ingredients with a focus on cost, availability, transportation, and dependability in MKW, WP, Indonesia.
2. To integrate LP, ingredient nutrient composition, and supply chain analysis in optimising livestock diet formulation based on poultry nutrient requirements, ingredient availability, and related costs in MKW, WP, Indonesia.
3. To assess the profitability and cost-effectiveness of imported and locally produced ingredients in feed formulations in order to lessen reliance on imported ingredients in the supply chain in MKW, WP, Indonesia.

3.2 Research Design

This study will be in the form of quantitative and applied research. According to Hammond and Wellington (2021), applied research is research designed to provide information or directed towards solving a problem that is immediately applicable and useful. Similarly, Saunders et al. (2012) stated that the purpose of applied research includes improving an

understanding of a particular management or business problem, resulting in solutions to problems and findings of practical consequences and value to managers in organisations.

Furthermore, quantitative research involves quantitative data, which can be measured less or more accurately because it is usually expressed in the form of numbers (Hammond & Wellington, 2021; Walliman, 2022). Quantitative data is associated with methodologies such as systematic review, surveys, meta-analysis, experimental methods, big data, and secondary data analysis (O’Gorman & MacIntosh, 2015), quantitative studies have four main characteristics:

- (1) reconstructed/systematic logic and linear path (step-by-step straight line)
- (2) hard data in nature (e.g. numbers)
- (3) relying on positivist principles, emphasising measuring variables and testing hypotheses
- (4) falsifying or verifying an existing relationship or hypothesis.

The main point of quantitative data is that it is in a number format, but the numbers may need to be cleaned up in appropriate formats for accuracy and analysis (Hammond & Wellington, 2021). Quantitative data can be analysed by using mathematical procedures or models to interpret the numerical data (Walliman, 2022). Quantitative data can be analysed through algebraic techniques that help to model business situations (Buglear, 2012). One algebraic technique applied in LP modelling to help find the solution to given situations and constraints (Buglear, 2012).

The research focused on optimising livestock diet formulation utilising LP modelling and ingredient nutrient composition values for poultry while investigating the supply chain of the selected feed ingredients in WP, Indonesia. Integrating LP modelling, ingredient nutrient composition values, and supply chain analysis can ensure that rations for poultry at different production stages meet the nutrient requirements while analysing the challenges of the feed supply chain. In addition, the supply chain analysis in this research incorporated the availability of the ingredients, logistics, economic considerations, and correlated costs. This design was selected because it offers practical solutions for optimising poultry diet formulation in limited and challenging environments (Hammond & Wellington, 2021; Walliman, 2022), including in WP, Indonesia. In the context of current research, the approach of integrating nutritional requirements of feed ingredients, utilising LP and the ingredient

nutrient composition values, and analysing the supply chain factors can provide quantitative-driven results.

3.3 Study Area Selection

The primary focus of this study is WP; however, MKW, as the capital city of WP, serves as a key reference location throughout this research. When comparing to major ports in Indonesia, some ports in WP contributed to the significant volume and value of exports by loading ports in the country (Statistics WP, 2025). MKW has a strategic position as the centre of logistics and distribution of many goods from inter-islands within WP, to other provinces in Papua Island or from other regions in Indonesia (Statistics WP, 2025). For the shipment from other islands in Indonesia and overseas, MKW dominates the market in WP. MKW was the largest number of arrival and departure airlines via the airport in 2023, with over 2,700 departures and embarkations in WP (Statistics WP, 2025). The data has shown that MKW has the highest domestic and overseas GRT (Gross Register Tonnage) at 6,212,594 and 312,814, respectively, with a total of 1,233 vessel visits in WP in 2024 (Statistics WP, 2025). This data has suggested that MKW has strategically utilised maritime infrastructure for logistics and the domestic economy. Thus, due to the centre of logistics and distribution, MKW in WP was chosen for this study.

Another reason WP was chosen is due to the potential ingredient availability in this region. Regarding ingredient availability, there are some ingredients in their original forms incorporated in this research diet found in WP. A variety of literature has stated that WP-produced commodities like maize (Statistics Indonesia, 2025; Syaranamual & Muyan, 2024), soybeans (MAI, 2023; Syaranamual & Muyan, 2024), cassava (MAI, 2023; Statistics Indonesia, 2025), rice (Statistics Indonesia, 2025; Syaranamual & Muyan, 2024), fish (Statistics WP, 2025), copra meal (Killian et al., 2022), palm oil (Hutabarat, 2024; Iyai et al., 2023), and limestone (Lukman et al., 2020). Some of these ingredients can be found in their original forms in WP but are still further processed for use in the feed formulation.

West Papua Province was chosen due to an increasing trend in the poultry population. Statistics Indonesia (2025) has reported that the poultry population has increased in different types of birds from 2023 to 2024 WP, including 163,900 to 177,023 native chickens, 65,659 to

77,571 layers, and 299,616 to 424,740 broilers. These data have shown that WP has a more promising future for the feed industry in the region.

In summary, MKW in WP offers a strategic position due to having the potential volume and value of exporting goods by the loading port. Some available feed ingredients incorporated in the research diet formulations can be found in their natural forms and produced in WP. Furthermore, there has been an increase in the poultry population in WP. Therefore, WP has been selected for this research due to these reasons.

3.4 Data Collection

This study uses data from secondary sources. Secondary data are data that have been collected for some other purposes (Saunders et al., 2012). Secondary data may be raw, where it needs further processing or compiled data that has received summarising or some form of selection (Saunders et al., 2012). According to Saunders et al. (2012), multiple-source secondary data can be compiled entirely from survey data or documentary data or can be an amalgam of the two. The secondary data used in this study were derived from multiple sources. These multiple sources have been stated in Saunders et al. (2012), which include snapshots and longitudinal data. Snapshots to form cohort studies include government publications, books, and journal articles. In comparison, longitudinal data includes industry statistics and reports, government publications, surveys from censuses like the government census of population, continuous and regular surveys like the labour market, and trends (Saunders et al., 2012).

Sources like online databases, university databases, survey reports, quality national newspapers, and government websites can provide the secondary data needed. Quality national newspapers are a good source of information, providing recent reports, including their findings and report summaries, and recent events in the business world (Saunders et al., 2012). Furthermore, Saunders et al. (2012) mentioned that the use of relevant web-based materials generated by online communities can be utilised, with some cases charging a subscription and additional administrative and royalty charges. Moreover, even though data from government websites and sources are usually of good quality, those from other sources may be neither reliable nor valid. Thus, it is critical to evaluate the suitability of the secondary data in the research (Saunders et al., 2012). Although the data collected may originally have

had different purposes, the data collected in this research suit this research's purposes (Buglear, 2012). Additionally, Buglear (2012) added that it is essential to acknowledge the sources of the secondary data being used. These secondary sources can provide decent information with careful consideration of reliability and validity.

Varied sources of secondary data have advantages and drawbacks. Based on Saunders et al. (2012), secondary data has several advantages, such as being unobtrusive, resulting in unforeseen discoveries, being permanent data, providing contextual and comparative data, making longitudinal studies feasible, and they may have fewer resource requirements. The secondary data benefits the research by saving the time and expense of collecting data while still providing context and fundamental data for this research (Hammond & Wellington, 2021). On the other hand, the drawbacks include data collected for a purpose that does not match the new researchers' needs; access may be difficult or costly; aggregations and definitions may be unsuitable; no real control over data quality; and initial purpose may affect how data are presented (Saunders et al., 2012). Correspondingly, the use of varied sources of secondary data must be linked back to the research purpose to maximise the quality of the research.

With a thorough assessment, the first step in conducting this research was to select the feed ingredients that are available locally in WP, other regions in Indonesia, and the imported ingredients. The second step is to gather the ingredient nutrient composition or feedstuff matrix values from the Evonik Industries AG's book (2016) and a variety of sources, then input the values into the Microsoft Excel spreadsheets. The Evonik book (2016) is the primary reference for SID values, which are vital to providing values for the selected ingredients' digestibility and nutrient utilisation by poultry (Evonik Industries AG, 2016). Meanwhile, the Microsoft Excel spreadsheet is a popular tool for solving and analysing small LP problems (Hillier & Lieberman, 2005). The spreadsheets can be used to analyse potential solutions quickly by inputting some additional information (Hillier & Lieberman, 2005). If some nutrient content or SID values were missing in the Evonik Book, the missing data were collected from reputable scientific journals and academic literature. These scientific journals and academics provided broilers and layers requirements values, the limitation factors, constraints, and the minimum and the maximum ration of ingredients. For the other data related, including ingredient costs and availability, the data was collected from a variety of sources such as

government reports, industry websites, market databases, news outlets and publications, and scientific journals and academic literature. These data are critical to conducting the research.

Furthermore, the data on ingredient prices were based on market data in 2025. These prices are subject to fluctuations; future research needs to adjust regarding this matter. Exchange rate for 1 NZD (New Zealand Dollar) equals 9,551 IDR (Indonesian Rupiah) on 23 August 2025, 03:06 UTC. This research provides a modelling basis for least-cost diet formulation while considering the supply chain of the feed ingredients.

The next step to demonstrate the diet formulation model is organising the Excel worksheet, separating cells to show decision variables, forming a formula to show the objective function, and forming a formula in a cell to show all hand-side constraints (Aboudhier, 2017). The model is applied in an Excel worksheet; then, the “Solver add-in for Microsoft Excel” is used to find the solution (Aboudhier, 2017). In the Solver add-in, it is necessary to identify the objective function locations (cells), the decision variable, the objective function nature (maximise/minimise) and constraints (Aboudhier, 2017). This is where LP modelling techniques are utilised to acquire the best possible mixture of goods that leads to an increase in profitability and a decrease in costs in the presence of numerous restrictions, and to allocate limited resources among a number of goods (Aboudhier, 2017).

Table 1 exhibits the ingredients’ nutrient composition or feedstuff matrix used in the Excel worksheet used in this research. This feedstuff matrix is used against the constraints and selected poultry requirements. Tables 2, 4 and 6 show the dietary requirements for broilers, layers at the lower energy limit and layers at the upper energy limit, respectively. Tables 3 and 5 show the ingredient inclusion levels for broilers and layers, respectively. The ingredient inclusion levels mean a percentage of an ingredient included in the diet. In this research, the inclusion level was set to the maximum limit to prevent adverse effects. There are some references in “Constraint” or limitation that show “>” means “more than”, “<” means “less than”, and “=” means “equals to” against the ingredient inclusion levels. In Tables 3 to 5, some nutrient compositions like DM, ash, GE, Fat, starch, NDF, and ADF were intentionally put as zero after the “>” symbol to include the nutrient in the result of LP modelling without limiting the lower and upper bound of formulations to these nutrient compositions. The weight was all put as 1, meaning that the formulation in this research is per 1 kg of total feed amount.

Table 1
Ingredients Nutrient Composition

Ingredients Nutrient Composition		Maize	Wheat	RB	CRM	SBM	MBM	FM	CM	BSFL	CLM
		SID	SID	SID	SID	SID	SID	SID	SID	Data on as fed basis	Data on as fed basis
NZD/kg	COST	0.86 ¹	11.73 ²	0.79 ³	0.63 ⁴	1.59 ⁴	1.78 ⁴	1.787 ⁴	0.52 ⁵	8.29 ⁶	7.35 ⁶
Weight		1	1	1	1	1	1	1	1	1	1
DM	g/kg	880 ⁷	880 ⁷	880 ⁷	880 ⁷	880 ⁷	910 ⁷	910 ⁷	880 ⁷	917 ⁸	930 ⁹
Ash	g/kg	11.9 ⁷	17 ⁷	83.7 ⁷	28 ⁷	65.4 ⁷	312.8 ⁷	190.9 ⁷	70.7 ⁷	118 ⁸	85 ⁹
GE	MJ/kg	16.39 ⁷	16.14 ⁷	17.79 ⁷	15.04 ⁷	17.52 ⁷	15.51 ⁷	18.56 ⁷	15.72 ⁷	19.9 ⁸	19.7 ¹³
CP	g/kg	76 ⁷	117 ⁷	118 ⁷	26 ⁷	465 ⁷	468 ⁷	603 ⁷	216 ⁷	519 ⁸	210 ⁹
Fat	g/kg	37 ⁷	19.3 ⁷	140.5 ⁷	5.4 ⁷	21.6 ⁷	108 ⁷	100.1 ⁷	8.5 ⁷	110 ⁸	55 ⁹
Starch	g/kg	646.3 ⁷	602.2 ⁷	272.6 ⁷	734.8 ⁷	8 ⁷	-	-	3 ⁸	8 ⁸	17 ¹³
NDF	g/kg	105.5 ⁷	116.1 ⁷	206 ⁷	41.7 ⁷	118.9 ⁷	-	-	504.5 ⁷	220 ⁸	422 ¹³
ADF	g/kg	29.8 ⁷	31.8 ⁷	93.4 ⁷	34.5 ⁷	70.7 ⁷	-	-	231.7 ⁷	122 ⁸	310 ¹³
Ca	g/kg	0.1 ⁷	0.4 ⁷	0.5 ⁷	1.3 ⁷	2.9 ⁷	105 ⁷	49.3 ⁷	0.9 ⁷	39.6 ⁸	14.5 ⁹
Ca	g/kg	0.1 ⁷	0.4 ⁷	0.5 ⁷	1.3 ⁷	2.9 ⁷	105 ⁷	49.3 ⁷	0.9 ⁷	39.6 ⁸	14.5 ⁹
Mg	g/kg	0.9 ⁷	1 ⁷	7.1 ⁷	0.8 ⁷	2.9 ⁷	2.3 ⁷	2.3 ⁷	3 ⁷	3.5 ⁸	4.2 ⁹
Mg	g/kg	0.9 ⁷	1 ⁷	7.1 ⁷	0.8 ⁷	2.9 ⁷	2.3 ⁷	2.3 ⁷	3 ⁷	3.5 ⁸	4.2 ⁹
K	g/kg	3.1 ⁷	3.7 ⁷	12.6 ⁷	8.1 ⁷	20.5 ⁷	3.6 ⁷	8.1 ⁷	24.3 ⁷	9.6 ⁸	12.8 ⁹
K	g/kg	3.1 ⁷	3.7 ⁷	12.6 ⁷	8.1 ⁷	20.5 ⁷	3.6 ⁷	8.1 ⁷	24.3 ⁷	9.6 ⁸	12.8 ⁹
Na	g/kg	0.2 ¹⁰	0.1 ¹⁰	0.1 ⁷	0.1 ⁷	0.1 ⁷	7.2 ⁷	10.1 ⁷	0.7 ⁷	1.42 ⁸	0.2 ⁹
Na	g/kg	0.2 ¹⁰	0.1 ¹⁰	0.1 ⁷	0.1 ⁷	0.1 ⁷	7.2 ⁷	10.1 ⁷	0.7 ⁷	1.42 ⁸	0.2 ⁹
AvP	g/kg	2.2 ⁷	2.6 ⁷	14.3 ⁷	0.9 ⁷	5.9 ⁷	48.9 ⁷	27.9 ⁷	5.7 ⁷	6.3 ⁸	3.2 ¹³
AvP	g/kg	2.2 ⁷	2.6 ⁷	14.3 ⁷	0.9 ⁷	5.9 ⁷	48.9 ⁷	27.9 ⁷	5.7 ⁷	6.3 ⁸	3.2 ¹³
AMEn	MJ/kg	13.9 ⁷	12.91 ⁷	11.94 ⁷	13.1 ⁷	9.75 ⁷	9.64 ⁷	12.71 ⁷	5.43 ⁷	13.7 ⁸	7.8 ¹³
Arg	g/kg	3.2 ⁷	4.9 ⁷	7.1 ⁷	0.5 ⁸	31.1 ⁷	24.5 ⁷	29.8 ⁷	18.7 ⁷	22.7 ⁸	5.3 ⁹
His	g/kg	2.1 ⁷	2.4 ⁷	2.5 ⁷	0.5 ⁸	10.9 ⁷	4.9 ⁷	11.2 ⁷	2.7 ⁷	9.3 ⁸	2.3 ⁹
Iso	g/kg	2.5 ⁷	3.7 ⁷	2.7 ⁷	0.4 ⁸	18.4 ⁷	8.6 ⁷	19.6 ⁷	5.2 ⁷	20.1 ⁸	4.5 ⁹
Leu	g/kg	8.5 ⁷	7 ⁷	5.4 ⁷	0.7 ⁸	31 ⁷	17.9 ⁷	34.3 ⁷	10.3 ⁷	31.9 ⁸	8.2 ⁹
Lys	g/kg	2.1 ⁷	2.8 ⁷	4 ⁷	0.5 ⁸	25 ⁷	13.8 ⁷	35.6 ⁷	2.7 ⁷	24.7 ⁸	5.9 ⁹
Met	g/kg	1.5 ⁷	1.7 ⁷	1.7 ⁷	0.2 ⁸	5.6 ⁷	3.9 ⁷	13.1 ⁷	2.3 ⁷	8.4 ⁸	1.9 ⁹
Phe	g/kg	3.4 ⁷	4.8 ⁷	3.4 ⁷	0.5 ⁸	21 ⁷	10.2 ⁷	18.5 ⁷	7.4 ⁷	17.8 ⁸	5.4 ⁹
Thr	g/kg	2.4 ⁷	2.9 ⁷	2.9 ⁷	0.4 ⁸	14.9 ⁷	8.6 ⁷	19.1 ⁷	3.7 ⁷	17 ⁸	4.4 ⁹
Val	g/kg	3.4 ⁷	4.5 ⁷	4.3 ⁷	0.6 ⁸	19.2 ⁷	12.8 ⁷	22.7 ⁷	8.1 ⁷	27.7 ⁸	5.6 ⁹
Ala	g/kg	5.6 ¹⁰	3.3 ¹⁰	6.1 ¹⁰	0.7 ⁸	17.6 ¹⁰	33.3 ¹⁰	34.9 ⁷	5.4 ⁷	28.9 ⁸	6.1 ¹³
Asp	g/kg	3.5 ¹⁰	2.9 ¹⁰	4.8 ¹⁰	0.8 ⁸	29.3 ¹⁰	13.3 ¹⁰	25.7 ¹⁰	9.7 ⁷	37.6 ⁸	9.6 ¹³
Cys	g/kg	1.5 ⁷	2.4 ⁷	1.5 ⁷	0.2 ⁸	5.3 ⁷	1.3 ⁷	3.1 ⁷	1.5 ⁷	2.1 ⁸	0.8 ¹³
Glu	g/kg	5.1 ¹⁰	13.1 ¹⁰	5.8 ¹⁰	1.4 ⁸	42 ¹⁰	28 ¹⁰	38.3 ¹⁰	23.8 ⁸	45.4 ⁸	10.7 ¹³
Gly	g/kg	4 ¹⁰	4.4 ¹⁰	5.7 ¹⁰	0.4 ⁸	16.6 ¹⁰	62.8 ¹⁰	44.1 ¹⁰	5.4 ⁸	24.1 ⁸	5.2 ¹³
Pro	g/kg	6.4 ¹⁰	12.3 ¹⁰	4.4 ¹⁰	0.5 ⁸	21.1 ¹⁰	34.5 ¹⁰	24.1 ⁸	4 ⁸	26.6 ⁸	3.7 ¹³
Ser	g/kg	3.7 ¹⁰	4.9 ¹⁰	4.5 ¹⁰	0.4 ⁸	22.5 ¹⁰	15 ¹⁰	24.7 ¹⁰	5.7 ⁸	19 ⁸	4 ¹³
Tyr	g/kg	2.4 ¹⁰	2 ¹⁰	3.4 ¹⁰	0.3 ⁸	15 ¹⁰	7.6 ¹⁰	16.1 ¹⁰	2.7 ⁸	28.1 ⁸	3.9 ¹³

Table 1
Ingredients Nutrient Composition (Continued)

Ingredients Nutrient Composition		PO	LiSt	CaHPO ₄	Ca ₃ (PO ₄) ₂	L-Lys	DL-Met	L-Thre	NaCl	Na ₂ CO ₃	MP	VP
		Data on as fed basis	Data on as fed basis	Data on as fed basis	Data on as fed basis	Data on as fed basis	Data on as fed basis	Data on as fed basis	Data on as fed basis	Data on as fed basis		
NZD/kg	COST	1.67 ¹	0.06 ⁴	2.52 ⁵	7.35 ⁴	6.09 ⁴	11.79 ⁴	8.39 ⁴	0.80 ⁴	0.94 ⁴	3.59 ⁴	1.67 ⁴
Weight		1	1	1	1	1	1	1	1	1	1	1
DM	g/kg	995 ¹⁰	980 ¹¹	970 ⁸	992 ⁸	995 ⁸	995 ⁸	995 ⁸	980 ¹¹	980 ¹¹	1000 ¹²	1000 ¹²
Ash	g/kg	-	-	885 ⁸	974 ⁸	-	-	-	-	-	-	-
GE	MJ/kg	39.33 ¹⁰	-	-	-	20 ⁸	23.6 ⁸	17.2 ⁸	-	-	-	-
CP	g/kg	-	-	-	-	954 ⁸	584 ⁸	731 ⁸	-	-	-	-
Fat	g/kg	995 ¹⁰	-	-	-	-	-	-	-	-	-	-
Starch	g/kg	-	-	-	-	-	-	-	-	-	-	-
NDF	g/kg	-	-	-	-	-	-	-	-	-	-	-
ADF	g/kg	-	-	-	-	-	-	-	-	-	-	-
Ca	g/kg	-	380 ¹¹	272 ⁸	367 ⁸	-	-	-	3 ¹¹	-	-	-
Ca	g/kg	-	380 ¹¹	272 ⁸	367 ⁸	-	-	-	3 ¹¹	-	-	-
Mg	g/kg	-	21 ¹¹	5.9 ⁸	-	-	-	-	0.05 ¹¹	-	-	-
Mg	g/kg	-	21 ¹¹	5.9 ⁸	-	-	-	-	0.05 ¹¹	-	-	-
K	g/kg	-	1 ¹¹	2.2 ⁸	-	-	-	-	-	-	-	-
K	g/kg	-	1 ¹¹	2.2 ⁸	-	-	-	-	-	-	-	-
Na	g/kg	-	0.5 ¹¹	2.52 ⁸	43.21 ⁸	-	-	-	390 ¹¹	433.9 ¹¹	-	-
Na	g/kg	-	0.5 ¹¹	2.52 ⁸	43.21 ⁸	-	-	-	390 ¹¹	433.9 ¹¹	-	-
AvP	g/kg	-	-	112 ⁸	138 ⁸	-	-	-	-	-	-	-
AvP	g/kg	-	-	112 ⁸	138 ⁸	-	-	-	-	-	-	-
AMEn	MJ/kg	36.89 ¹⁰	-	-	-	14 ⁸	19.4 ⁸	12.6 ⁸	-	-	-	-
Arg	g/kg	-	-	-	-	-	-	-	-	-	-	-
His	g/kg	-	-	-	-	-	-	-	-	-	-	-
Iso	g/kg	-	-	-	-	-	-	-	-	-	-	-
Leu	g/kg	-	-	-	-	-	-	-	-	-	-	-
Lys	g/kg	-	-	-	-	798 ⁸	-	-	-	-	-	-
Met	g/kg	-	-	-	-	-	990 ⁸	-	-	-	-	-
Phe	g/kg	-	-	-	-	-	-	-	-	-	-	-
Thr	g/kg	-	-	-	-	-	-	990 ⁸	-	-	-	-
Val	g/kg	-	-	-	-	-	-	-	-	-	-	-
Ala	g/kg	-	-	-	-	-	-	-	-	-	-	-
Asp	g/kg	-	-	-	-	-	-	-	-	-	-	-
Cys	g/kg	-	-	-	-	-	-	-	-	-	-	-
Glu	g/kg	-	-	-	-	-	-	-	-	-	-	-
Gly	g/kg	-	-	-	-	-	-	-	-	-	-	-
Pro	g/kg	-	-	-	-	-	-	-	-	-	-	-
Ser	g/kg	-	-	-	-	-	-	-	-	-	-	-
Tyr	g/kg	-	-	-	-	-	-	-	-	-	-	-

Note:

Rice Bran (RB)
Meat and Bone Meal (MBM)
Black Soldier Fly Larvae (BSFL)
Limestone (LiSt)
Levo Lystine (L-Lys)
Sodium Chloride/Salt (NaCl)

Cassava Root Meal (CRM)
Fish Meal (FM)
Cassava Leaf Meal (CLM)
CaHPO₄ (Dicalcium Phosphate)
Dextro Levo Methionine (DL-Met)
Sodium Carbonate (Na₂CO₃)

Soybean Meal (SBM)
Copra Meal (CM)
Palm Oil (PO)
Ca₃(PO₄)₂ (Tricalcium Phosphate)
Levo Threonine (L-Thre)
Mineral Premix (MP)

Vitamin Premix (VP)	Standardised Ileal Digestibility (SID)	NZD per kilogram (New Zealand Dollar/kg)
Dry Matter (DM)	gram per kilogram (g/kg)	Megajoule per kilogram (MJ/kg)
Gross Energy (GE)	Crude Protein (CP)	Neutral Detergent Fiber (NDF)
Acid Detergent Fiber (ADF)	Calcium (Ca)	Magnesium (Mg)
Potassium (K)	Sodium (Na)	Available Phosphorus (AvP)
AME Corrected for Nitrogen (AMEn)	Arginine (Arg)	Histidine (His)
Isoleucine (Iso)	Leucine (Leu)	Lysine (Lys)
Methionine (Met)	Phenylalanine (Phe)	Threonine (Thr)
Valine (Val)	Alanine (Ala)	Aspartic Acid (Asp)
Cysteine (Cys)	Glutamic Acid (Glu)	Glycine (Gly)
Proline (Pro)	Serine (Ser)	Tyrosine (Tyr)

Sources:

¹ Badan Pangan Nasional (2025).

² Data collected were unavailable for WP. However, available data were for JKT and SBY in Indonesia (Selina Wamucii, 2025). The price was then doubled to WP (Mahasyahputra et al., 2023).

³ Kartika (2025).

⁴ Data collected were unavailable for WP. However, available data were for JKT and SBY in Indonesia (Indotrading, 2025). The price was then doubled to WP (Mahasyahputra et al., 2023).

⁵ Killian et al. (2022).

⁶ Tokopedia (2025).

⁷ Evonik Industries AG (2016).

⁸ INRAE CIRAD AFZ (2024).

⁹ Ravindran (1992).

¹⁰ Rostagno et al. (2017).

¹¹ NRC (1994).

¹² Reiling (2022).

¹³ Feedipedia (2025).

Table 2
Dietary Requirements for Broilers

Dietary Requirements		Constraint	Nutrition Specifications for As-Hatched Broilers Target Live Weight >3.5 kg (>7.7 lb) ¹				
			Starter	Grower	Finisher 1	Finisher 2	Finisher 3
		Broilers	Days 0-10	Days 11-24	Days 25-39	Days 40-51	Days 52-market
Weight		=	1	1	1	1	1
DM	g/kg	>	0	0	0	0	0
Ash	g/kg	>	0	0	0	0	0
GE	MJ/kg	>	0	0	0	0	0
CP	g/kg	>	230 ¹	215 ¹	195 ¹	180 ¹	170 ¹
Fat	g/kg	>	0	0	0	0	0
Starch	g/kg	>	0	0	0	0	0
NDF	MJ/kg	>	0	0	0	0	0
ADF	g/kg	>	0	0	0	0	0
Ca	g/kg	>	9.5 ¹	7.5 ¹	6.5 ¹	6 ¹	5.5 ¹
Ca	g/kg	<	13 ²	13 ²	11.8 ²	11.8 ²	11.8 ²
Mg	g/kg	>	0.5 ¹	0.5 ¹	0.5 ¹	0.5 ¹	0.5 ¹
Mg	g/kg	<	3 ¹	3 ¹	3 ¹	3 ¹	3 ¹
K	g/kg	>	6 ¹	6 ¹	6 ¹	6 ¹	6 ¹
K	g/kg	<	9 ¹	9 ¹	9 ¹	9 ¹	9 ¹
Na	g/kg	>	1.8 ¹	1.8 ¹	1.8 ¹	1.8 ¹	1.8 ¹
Na	g/kg	<	2.3 ¹	2.3 ¹	2.3 ¹	2.3 ¹	2.3 ¹
AvP	g/kg	>	4.5 ³	4.1 ³	3.6 ¹	3.4 ¹	3 ³
AvP	g/kg	<	5 ¹	4.2 ¹	3.8 ³	3.6 ³	3.2 ¹
AMEn	MJ/kg	=	12.4 ¹	12.8 ¹	13 ¹	13.1 ¹	13.2 ¹
Arg	g/kg	>	14 ¹	12.7 ¹	11.7 ¹	11.2 ¹	10.8 ¹
His	g/kg	>	0 ¹	0 ¹	0 ¹	0 ¹	0 ¹
Iso	g/kg	>	8.8 ¹	8 ¹	7.5 ¹	7 ¹	6.7 ¹
Leu	g/kg	>	14.5 ¹	13 ¹	11.9 ¹	11.2 ¹	10.6 ¹
Lys	g/kg	=	13.2 ¹	11.8 ¹	10.8 ¹	10.2 ¹	9.6 ¹
Met	g/kg	>	5.5 ¹	5.1 ¹	4.8 ¹	4.5 ¹	4.2 ¹
Phe	g/kg	>	0 ¹	0 ¹	0 ¹	0 ¹	0 ¹
Thr	g/kg	>	8.8 ¹	7.9 ¹	7.2 ¹	6.8 ¹	6.4 ¹
Val	g/kg	>	10 ¹	9.1 ¹	8.4 ¹	8 ¹	7.7 ¹
Ala	g/kg	>	0 ¹	0 ¹	0 ¹	0 ¹	0 ¹
Asp	g/kg	>	0 ¹	0 ¹	0 ¹	0 ¹	0 ¹
Cys	g/kg	>	0 ¹	0 ¹	0 ¹	0 ¹	0 ¹
Glu	g/kg	>	0 ¹	0 ¹	0 ¹	0 ¹	0 ¹
Gly	g/kg	>	0 ¹	0 ¹	0 ¹	0 ¹	0 ¹
Pro	g/kg	>	0 ¹	0 ¹	0 ¹	0 ¹	0 ¹
Ser	g/kg	>	0 ¹	0 ¹	0 ¹	0 ¹	0 ¹
Tyr	g/kg	>	0 ¹	0 ¹	0 ¹	0 ¹	0 ¹

Sources:

¹ Aviagen Group (2022)

² NRC (1994)

³ Leeson and Summers (2005)

⁴ Ravindran (2013)

⁵ Vilela et al. (2023)

⁶ Diarra and Devi (2015)

⁷ Long et al. (2019)

⁸ European Commission (2003)

⁹ Reiling (2022)

Table 3
Ingredient Inclusion Levels for Broilers

Ingredient Inclusion Levels		Constraint	Nutrition Specifications for As-Hatched Broilers Target Live Weight >3.5 kg (>7.7 lb) ¹				
			Starter	Grower	Finisher 1	Finisher 2	Finisher 3
		Broilers	Days 0-10	Days 11-24	Days 25-39	Days 40-51	Days 52-market
Ingredient Inclusion Levels							
Maize	%	<	60 ³	60 ³	70 ³	70 ³	70 ³
Wheat	%	<	15 ³	20 ³	25 ³	25 ³	25 ³
RB	%	<	10 ³	10 ³	20 ³	20 ³	20 ³
CRM	%	<	40 ⁴	40 ⁴	40 ⁴	40 ⁴	40 ⁴
SBM	%	<	30 ³	30 ³	30 ³	30 ³	30 ³
MBM	%	<	6 ³	6 ³	8 ³	8 ³	8 ³
FM	%	<	8 ³	8 ³	10 ³	10 ³	10 ³
CM	%	<	20 ⁴	20 ⁴	20 ⁴	20 ⁴	20 ⁴
BSFL	%	<	20 ⁵	20 ⁵	20 ⁵	20 ⁵	20 ⁵
CLM	%	<	20 ⁶	20 ⁶	20 ⁶	20 ⁶	20 ⁶
PO	%	<	6 ⁷	6 ⁷	6 ⁷	6 ⁷	6 ⁷
LiSt	%	<	3 ⁴	3 ⁴	3 ⁴	3 ⁴	3 ⁴
CaHPO ₄	%	<	1.5 ⁸	1.5 ⁸	1.5 ⁸	1.5 ⁸	1.5 ⁸
Ca ₃ (PO ₄) ₂	%	<	1.5 ⁸	1.5 ⁸	1.5 ⁸	1.5 ⁸	1.5 ⁸
L-Lys	%	<	1.1 ²	1.1 ²	1 ²	0.85 ²	0.85 ²
DL-Met	%	<	0.5 ²	0.5 ²	0.38 ²	0.32 ²	0.32 ²
L-Thre	%	<	0.8 ²	0.8 ²	0.74 ²	0.68 ²	0.68 ²
NaCl	%	<	0.4 ⁴	0.4 ⁴	0.4 ⁴	0.4 ⁴	0.4 ⁴
Na ₂ CO ₃	%	<	0.4 ⁴	0.4 ⁴	0.4 ⁴	0.4 ⁴	0.4 ⁴
MP	%	=	1 ⁹	1 ⁹	1 ⁹	1 ⁹	1 ⁹
VP	%	=	1 ⁹	1 ⁹	1 ⁹	1 ⁹	1 ⁹

Sources:

¹ Aviagen Group (2022)

² NRC (1994)

³ Leeson and Summers (2005)

⁴ Ravindran (2013)

⁵ Vilela et al. (2023)

⁶ Diarra and Devi (2015)

⁷ Long et al. (2019)

⁸ European Commission (2003)

⁹ Reiling (2022)

Table 4
Dietary Nutrient Requirements for Layers at the Lower Energy Limit

Dietary Requirements		Constraint	Rearing Period and Production Periods Nutritional Recommendations for Hy-Line Brown Max Layers (for Economical Performance) at Lower Limit Energy Requirement									
			Starter 1	Starter 2	Grower	Developer	Pre-lay	Peaking	Layer 2	Layer 3	Layer 4	Layer 5
		Layers	Body weight of 205g (Days 0-20/Week 0-3)	Body weight of 495g (Days 21-41/Week 3-6)	Body weight of 1150g (Days 42-83/Week 6-12)	Body weight of 1395g (Days 84-104/Week 12-15)	Body weight of 1538g (Days 105-118/Week 15-17)	First egg until production drops 2% below peak (Days 119-251/Week 17-36)	2% below peak - 92% (Days 252-293/Week 36-42)	91-88% (Days 294-384/Week 42-55)	87-83% (Days 385-482/Week 55-69)	Less than 83% (Days 483-700/Week 69-100)
Weight		=	1	1	1	1	1	1	1	1	1	1
DM	g/kg	>	0	0	0	0	0	0	0	0	0	0
Ash	g/kg	>	0	0	0	0	0	0	0	0	0	0
GE	MJ/kg	>	0	0	0	0	0	0	0	0	0	0
CP	g/kg	>	200 ¹	180 ¹	170 ¹	155 ¹	165 ¹	178 ¹	160 ¹	151.8 ¹	148.2 ¹	140.9 ¹
Fat	g/kg	>	0	0	0	0	0	0	0	0	0	0
Starch	g/kg	>	0	0	0	0	0	0	0	0	0	0
NDF	g/kg	>	0	0	0	0	0	0	0	0	0	0
ADF	g/kg	>	0	0	0	0	0	0	0	0	0	0
Ca	g/kg	>	9 ²	9 ²	8 ²	8 ²	18 ²	33.3 ¹	35 ¹	36.7 ¹	38.3 ¹	39.2 ¹
Ca	g/kg	<	10.5 ¹	10 ¹	9.5 ¹	9 ¹	25 ¹	44.4 ¹	42 ¹	44 ¹	46 ¹	47 ¹
Mg	g/kg	>	0 ¹	0 ¹	0 ¹	0 ¹	0 ¹	0 ¹	0 ¹	0 ¹	0 ¹	0 ¹
Mg	g/kg	>	0 ¹	0 ¹	0 ¹	0 ¹	0 ¹	0 ¹	0 ¹	0 ¹	0 ¹	0 ¹
K	g/kg	>	0 ¹	0 ¹	0 ¹	0 ¹	0 ¹	0 ¹	0 ¹	0 ¹	0 ¹	0 ¹
K	g/kg	>	0 ¹	0 ¹	0 ¹	0 ¹	0 ¹	0 ¹	0 ¹	0 ¹	0 ¹	0 ¹
Na	g/kg	>	1.5 ²	1.5 ²	1.5 ²	1.5 ²	1.5 ²	1.6 ¹	1.4 ¹	1.4 ¹	1.4 ¹	1.4 ¹
Na	g/kg	<	1.8 ¹	1.8 ¹	1.8 ¹	1.8 ¹	1.8 ¹	2 ¹	1.7 ¹	1.7 ¹	1.7 ¹	1.7 ¹
AvP	g/kg	>	4.4 ³	3.9 ³	3.9 ³	3.8 ¹	4.2 ¹	3.6 ¹	3.4 ¹	3.1 ¹	2.9 ¹	2.7 ¹
AvP	g/kg	<	4.5 ¹	4.4 ¹	4.3 ¹	3.9 ³	4.3 ³	4.8 ¹	4.1 ¹	3.7 ¹	3.5 ¹	3.2 ¹
AMEn	MJ/kg	=	12.13 ¹	11.92 ¹	11.72 ¹	11.3 ¹	11.51 ¹	13.2 ¹	13 ¹	12.8 ¹	12.6 ¹	12.6 ¹
Arg	g/kg	>	11.1 ¹	9.6 ¹	8.5 ¹	6.3 ¹	7.5 ¹	8.6 ¹	7.7 ¹	7.4 ¹	7 ¹	6.6 ¹
His	g/kg	>	0 ¹	0 ¹	0 ¹	0 ¹	0 ¹	0 ¹	0 ¹	0 ¹	0 ¹	0 ¹
Iso	g/kg	>	7.5 ¹	6.6 ¹	6.1 ¹	4.5 ¹	5.6 ¹	6.6 ¹	5.9 ¹	5.7 ¹	5.4 ¹	5.1 ¹
Leu	g/kg	>	0 ¹	0 ¹	0 ¹	0 ¹	0 ¹	0 ¹	0 ¹	0 ¹	0 ¹	0 ¹
Lys	g/kg	=	10.7 ¹	9.2 ¹	8.2 ¹	6 ¹	7.2 ¹	8.3 ¹	7.4 ¹	7.1 ¹	6.8 ¹	6.4 ¹
Met	g/kg	>	4.8 ¹	4.2 ¹	3.9 ¹	2.8 ¹	3.5 ¹	4.2 ¹	3.7 ¹	3.5 ¹	3.4 ¹	3.2 ¹
Phe	g/kg	>	0 ¹	0 ¹	0 ¹	0 ¹	0 ¹	0 ¹	0 ¹	0 ¹	0 ¹	0 ¹
Thr	g/kg	>	6.9 ¹	6 ¹	5.5 ¹	4.1 ¹	5 ¹	5.8 ¹	5.2 ¹	5 ¹	4.7 ¹	4.5 ¹
Val	g/kg	>	7.7 ¹	6.8 ¹	6.4 ¹	4.8 ¹	6.1 ¹	7.3 ¹	6.5 ¹	6.2 ¹	6 ¹	5.6 ¹
Ala	g/kg	>	0 ¹	0 ¹	0 ¹	0 ¹	0 ¹	0 ¹	0 ¹	0 ¹	0 ¹	0 ¹
Asp	g/kg	>	0 ¹	0 ¹	0 ¹	0 ¹	0 ¹	0 ¹	0 ¹	0 ¹	0 ¹	0 ¹
Cys	g/kg	>	0 ¹	0 ¹	0 ¹	0 ¹	0 ¹	0 ¹	0 ¹	0 ¹	0 ¹	0 ¹
Glu	g/kg	>	0 ¹	0 ¹	0 ¹	0 ¹	0 ¹	0 ¹	0 ¹	0 ¹	0 ¹	0 ¹
Gly	g/kg	>	0 ¹	0 ¹	0 ¹	0 ¹	0 ¹	0 ¹	0 ¹	0 ¹	0 ¹	0 ¹
Pro	g/kg	>	0 ¹	0 ¹	0 ¹	0 ¹	0 ¹	0 ¹	0 ¹	0 ¹	0 ¹	0 ¹
Ser	g/kg	>	0 ¹	0 ¹	0 ¹	0 ¹	0 ¹	0 ¹	0 ¹	0 ¹	0 ¹	0 ¹
Tyr	g/kg	>	0 ¹	0 ¹	0 ¹	0 ¹	0 ¹	0 ¹	0 ¹	0 ¹	0 ¹	0 ¹

Sources:

¹ Hy-Line International (2023)² NRC (1994)³ Leeson and Summers (2001)⁴ Leeson and Summers (2005)⁵ Ravindran (2013)⁶ Patterson et al. (2021)⁷ Diarra and Devi (2015)⁸ Saminathan et al. (2020)⁹ Guo and Kim (2012)¹⁰ European Commission (2003)¹¹ Reiling (2022)

Table 5
 Ingredient Inclusion Levels for Layers at the Lower and Upper Energy Limits

Dietary Requirements		Cons traint	Rearing Period and Production Periods Nutritional Recommendations for Hy-Line Brown Max Layers (for Economical Performance) at Lower and Upper Limit Energy Requirement									
			Starter 1	Starter 2	Grower	Developer	Pre-lay	Peaking	Layer 2	Layer 3	Layer 4	Layer 5
		Layers	Body weight of 205g (Days 0-20/ Week 0-3)	Body weight of 495g (Days 21-41/ Week 3-6)	Body weight of 1150g (Days 42-83/ Week 6-12)	Body weight of 1395g (Days 84-104/ Week 12-15)	Body weight of 1538g (Days 105-118/ Week 15-17)	First egg until production drops 2% below peak (Days 119-251/ Week 17-36)	2% below peak - 92% (Days 252-293/ Week 36-42)	91-88% (Days 294-384/ Week 42-55)	87-83% (Days 385-482/ Week 55-69)	Less than 83% (Days 483-700/ Week 69-100)
Ingredient Inclusion Level												
Maize	%	<	60 ⁴	70 ⁴	70 ⁴	70 ⁴	70 ⁴	70 ⁴	70 ⁴	70 ⁴	70 ⁴	70 ⁴
Wheat	%	<	20 ⁴	25 ⁴	25 ⁴	25 ⁴	25 ⁴	25 ⁴	25 ⁴	25 ⁴	25 ⁴	25 ⁴
RB	%	<	10 ⁴	20 ⁴	20 ⁴	20 ⁴	20 ⁴	25 ⁴	25 ⁴	25 ⁴	25 ⁴	25 ⁴
CRM	%	<	40 ⁵	40 ⁵	40 ⁵	40 ⁵	40 ⁵	40 ⁵	40 ⁵	40 ⁵	40 ⁵	40 ⁵
SBM	%	<	30 ⁴	30 ⁴	30 ⁴	30 ⁴	30 ⁴	30 ⁴	30 ⁴	30 ⁴	30 ⁴	30 ⁴
MBM	%	<	6 ⁴	8 ⁴	8 ⁴	8 ⁴	8 ⁴	8 ⁴	8 ⁴	8 ⁴	8 ⁴	8 ⁴
FM	%	<	8 ⁴	10 ⁴	10 ⁴	10 ⁴	10 ⁴	10 ⁴	10 ⁴	10 ⁴	10 ⁴	10 ⁴
CM	%	<	20 ⁵	20 ⁵	20 ⁵	20 ⁵	20 ⁵	20 ⁵	20 ⁵	20 ⁵	20 ⁵	20 ⁵
BSFL	%	<	23.93 ⁶	23.93 ⁶	23.93 ⁶	23.93 ⁶	23.93 ⁶	23.93 ⁶	23.93 ⁶	23.93 ⁶	23.93 ⁶	23.93 ⁶
CLM	%	<	20 ⁷	20 ⁷	20 ⁷	20 ⁷	20 ⁷	20 ⁷	20 ⁷	20 ⁷	20 ⁷	20 ⁷
PO	%	<	5 ⁸	5 ⁸	5 ⁸	5 ⁸	5 ⁸	5 ⁸	5 ⁸	5 ⁸	5 ⁸	5 ⁸
LISt	%	<	10 ⁹	10 ⁹	10 ⁹	10 ⁹	10 ⁹	10 ⁹	10 ⁹	10 ⁹	10 ⁹	10 ⁹
CaHPO ₄	%	<	1.3 ¹⁰	1.3 ¹⁰	1.3 ¹⁰	1.3 ¹⁰	1.3 ¹⁰	1.3 ¹⁰	1.3 ¹⁰	1.3 ¹⁰	1.3 ¹⁰	1.3 ¹⁰
Ca ₃ (PO ₄) ₂	%	<	1.3 ¹⁰	1.3 ¹⁰	1.3 ¹⁰	1.3 ¹⁰	1.3 ¹⁰	1.3 ¹⁰	1.3 ¹⁰	1.3 ¹⁰	1.3 ¹⁰	1.3 ¹⁰
L-Lys	%	>	0.8 ²	0.8 ²	0.56 ²	0.42 ²	0.42 ²	0.49 ²	0.69 ²	0.69 ²	0.69 ²	0.69 ²
DL-Met	%	>	0.28 ²	0.28 ²	0.23 ²	0.19 ²	0.19 ²	0.21 ²	0.3 ²	0.3 ²	0.3 ²	0.3 ²
L-Thre	%	>	0.64 ²	0.64 ²	0.53 ²	0.35 ²	0.35 ²	0.44 ²	0.47 ²	0.47 ²	0.47 ²	0.47 ²
NaCl	%	<	0.4 ⁵	0.4 ⁵	0.4 ⁵	0.4 ⁵	0.4 ⁵	0.4 ⁵	0.4 ⁵	0.4 ⁵	0.4 ⁵	0.4 ⁵
Na ₂ CO ₃	%	<	0.4 ⁵	0.4 ⁵	0.4 ⁵	0.4 ⁵	0.4 ⁵	0.4 ⁵	0.4 ⁵	0.4 ⁵	0.4 ⁵	0.4 ⁵
MP	%	=	1 ¹¹	1 ¹¹	1 ¹¹	1 ¹¹	1 ¹¹	1 ¹¹	1 ¹¹	1 ¹¹	1 ¹¹	1 ¹¹
VP	%	=	1 ¹¹	1 ¹¹	1 ¹¹	1 ¹¹	1 ¹¹	1 ¹¹	1 ¹¹	1 ¹¹	1 ¹¹	1 ¹¹

Sources:

¹ Hy-Line International (2023)

² NRC (1994)

³ Leeson and Summers (2001)

⁴ Leeson and Summers (2005)

⁵ Ravindran (2013)

⁶ Patterson et al. (2021)

⁷ Diarra and Devi (2015)

⁸ Saminathan et al. (2020)

⁹ Guo and Kim (2012)

¹⁰ European Commission (2003)

¹¹ Reiling (2022)

Table 6
Dietary Requirements for Layers at the Upper Energy Limit

Dietary Requirements		Cons traint	Rearing Period and Production Periods Nutritional Recommendations for Hy-Line Brown Max Layers (for Economical Performance) at Lower Limit Energy Requirement									
			Starter 1	Starter 2	Grower	Developer	Pre-lay	Peaking	Layer 2	Layer 3	Layer 4	Layer 5
		Layers	Body weight of 205g (Days 0-20/ Week 0-3)	Body weight of 495g (Days 21-41/ Week 3-6)	Body weight of 1150g (Days 42-83/ Week 6-12)	Body weight of 1395g (Days 84-104/ Week 12-15)	Body weight of 1538g (Days 105-118/ Week 15-17)	First egg until production drops 2% below peak (Days 119-251/ Week 17-36)	2% below peak - 92% (Days 252-293/ Week 36-42)	91-88% (Days 294-384/ Week 42-55)	87-83% (Days 385-482/ Week 55-69)	Less than 83% (Days 483-700/ Week 69-100)
Weight		=	1	1	1	1	1	1	1	1	1	1
DM	g/kg	>	0	0	0	0	0	0	0	0	0	0
Ash	g/kg	>	0	0	0	0	0	0	0	0	0	0
GE	MJ/kg	>	0	0	0	0	0	0	0	0	0	0
CP	g/kg	>	200 ¹	180 ¹	170 ¹	155 ¹	165 ¹	178 ¹	160 ¹	151.8 ¹	148.2 ¹	140.9 ¹
Fat	g/kg	>	0	0	0	0	0	0	0	0	0	0
Starch	g/kg	>	0	0	0	0	0	0	0	0	0	0
NDF	g/kg	>	0	0	0	0	0	0	0	0	0	0
ADF	g/kg	>	0	0	0	0	0	0	0	0	0	0
Ca	g/kg	>	9 ²	9 ²	8 ²	8 ²	18 ²	33.3 ¹	35 ¹	36.7 ¹	38.3 ¹	39.2 ¹
Ca	g/kg	<	10.5 ¹	10 ¹	9.5 ¹	9 ¹	25 ¹	44.4 ¹	42 ¹	44 ¹	46 ¹	47 ¹
Mg	g/kg	>	0 ¹	0 ¹	0 ¹	0 ¹	0 ¹	0 ¹	0 ¹	0 ¹	0 ¹	0 ¹
Mg	g/kg	>	0 ¹	0 ¹	0 ¹	0 ¹	0 ¹	0 ¹	0 ¹	0 ¹	0 ¹	0 ¹
K	g/kg	>	0 ¹	0 ¹	0 ¹	0 ¹	0 ¹	0 ¹	0 ¹	0 ¹	0 ¹	0 ¹
K	g/kg	>	0 ¹	0 ¹	0 ¹	0 ¹	0 ¹	0 ¹	0 ¹	0 ¹	0 ¹	0 ¹
Na	g/kg	>	1.5 ²	1.5 ²	1.5 ²	1.5 ²	1.5 ²	1.6 ¹	1.4 ¹	1.4 ¹	1.4 ¹	1.4 ¹
Na	g/kg	<	1.8 ¹	1.8 ¹	1.8 ¹	1.8 ¹	1.8 ¹	2 ¹	1.7 ¹	1.7 ¹	1.7 ¹	1.7 ¹
AvP	g/kg	>	4.4 ³	3.9 ³	3.9 ³	3.8 ¹	4.2 ¹	3.6 ¹	3.4 ¹	3.1 ¹	2.9 ¹	2.7 ¹
AvP	g/kg	<	4.5 ¹	4.4 ¹	4.3 ¹	3.9 ³	4.3 ³	4.8 ¹	4.1 ¹	3.7 ¹	3.5 ¹	3.2 ¹
AMEn	MJ/kg	=	12.97 ¹	12.76 ¹	12.55 ¹	12.55 ¹	12.55 ¹	13.8 ¹	13.6 ¹	13.4 ¹	13.2 ¹	13.2 ¹
Arg	g/kg	>	11.1 ¹	9.6 ¹	8.5 ¹	6.3 ¹	7.5 ¹	8.6 ¹	7.7 ¹	7.4 ¹	7 ¹	6.6 ¹
His	g/kg	>	0 ¹	0 ¹	0 ¹	0 ¹	0 ¹	0 ¹	0 ¹	0 ¹	0 ¹	0 ¹
Iso	g/kg	>	7.5 ¹	6.6 ¹	6.1 ¹	4.5 ¹	5.6 ¹	6.6 ¹	5.9 ¹	5.7 ¹	5.4 ¹	5.1 ¹
Leu	g/kg	>	0 ¹	0 ¹	0 ¹	0 ¹	0 ¹	0 ¹	0 ¹	0 ¹	0 ¹	0 ¹
Lys	g/kg	=	10.7 ¹	9.2 ¹	8.2 ¹	6 ¹	7.2 ¹	8.3 ¹	7.4 ¹	7.1 ¹	6.8 ¹	6.4 ¹
Met	g/kg	>	4.8 ¹	4.2 ¹	3.9 ¹	2.8 ¹	3.5 ¹	4.2 ¹	3.7 ¹	3.5 ¹	3.4 ¹	3.2 ¹
Phe	g/kg	>	0 ¹	0 ¹	0 ¹	0 ¹	0 ¹	0 ¹	0 ¹	0 ¹	0 ¹	0 ¹
Thr	g/kg	>	6.9 ¹	6 ¹	5.5 ¹	4.1 ¹	5 ¹	5.8 ¹	5.2 ¹	5 ¹	4.7 ¹	4.5 ¹
Val	g/kg	>	7.7 ¹	6.8 ¹	6.4 ¹	4.8 ¹	6.1 ¹	7.3 ¹	6.5 ¹	6.2 ¹	6 ¹	5.6 ¹
Ala	g/kg	>	0 ¹	0 ¹	0 ¹	0 ¹	0 ¹	0 ¹	0 ¹	0 ¹	0 ¹	0 ¹
Asp	g/kg	>	0 ¹	0 ¹	0 ¹	0 ¹	0 ¹	0 ¹	0 ¹	0 ¹	0 ¹	0 ¹
Cys	g/kg	>	0 ¹	0 ¹	0 ¹	0 ¹	0 ¹	0 ¹	0 ¹	0 ¹	0 ¹	0 ¹
Glu	g/kg	>	0 ¹	0 ¹	0 ¹	0 ¹	0 ¹	0 ¹	0 ¹	0 ¹	0 ¹	0 ¹
Gly	g/kg	>	0 ¹	0 ¹	0 ¹	0 ¹	0 ¹	0 ¹	0 ¹	0 ¹	0 ¹	0 ¹
Pro	g/kg	>	0 ¹	0 ¹	0 ¹	0 ¹	0 ¹	0 ¹	0 ¹	0 ¹	0 ¹	0 ¹
Ser	g/kg	>	0 ¹	0 ¹	0 ¹	0 ¹	0 ¹	0 ¹	0 ¹	0 ¹	0 ¹	0 ¹
Tyr	g/kg	>	0 ¹	0 ¹	0 ¹	0 ¹	0 ¹	0 ¹	0 ¹	0 ¹	0 ¹	0 ¹

Sources:

¹ Hy-Line International (2023)

² NRC (1994)

³ Leeson and Summers (2001)

⁴ Leeson and Summers (2005)

⁵ Ravindran (2013)

⁶ Patterson et al. (2021)

⁷ Diarra and Devi (2015)

⁸ Saminathan et al. (2020)

⁹ Guo and Kim (2012)

¹⁰ European Commission (2003)

¹¹ Reiling (2022)

3.5 Data Analysis

After acquiring all the data, LP modelling was run in Microsoft Excel to formulate the least-cost diets. The values in the feedstuff matrix sheets were regularly updated because of the dynamics of cost and limitation factors of each ingredient. The LP model utilised the mathematical function to generate the least-cost outcome by incorporating key factors, including the nutritive values of ingredients, cost data, and ingredient inclusion levels against the nutritional requirements of poultry (Dryden, 2008), including its different phases of life. The outcomes generated after running the LP model varied shows the influence of the nutritive values of ingredients, ingredients availability, the related costs, and constraint elements. Dryden (2008) affirm that this method allows the results to be based on real-world problems due to its relationships with nutritional contents, availability, and the influence of cost and the supply chain.

3.6 Sensitivity Analysis

For the sensitivity analysis, this research will investigate supply chain disruptions by illustrating the unavailability of two ingredients, including maize and SBM. These ingredients were chosen because many studies indicate that maize and SBM are primary sources of energy and protein in many poultry diets worldwide (Cheeke, 2005; Leeson & Summers, 2005; Scanes & Christensen, 2020). This sensitivity modelling aims to determine whether the unavailability of these ingredients affects the identification of least-cost diet solutions and the overall diet cost. Additionally, three conditions will be examined: zero inclusion levels for maize only, SBM only, and both maize and SBM. In this demonstration, the diet with the highest combinations of maize and SBM from 25 formulated diets in this research will be selected—one diet for broilers and one for layers. These 25 diets will be referred to as initial diets. The approach of selecting the highest combinations of maize and SBM aims to represent the reliance on these ingredients, as their unavailability and substitution with other ingredients can significantly impact diet formulation and costs. Therefore, this approach is suitable for conducting a sensitivity analysis of the supply chain of feed ingredients incorporated in this research.

3.7 Validity, Reliability, and Transparency

The concepts of validity and reliability have significant implications for the way researchers think about their work (O’Gorman & MacIntosh, 2015). Since the data were collected entirely through secondary sources, the data may be for the present and explain why the changes in the field have reduced the usefulness of the data (Buglear, 2012). The validity concept can be seen in quantitative-based studies as both external and internal (O’Gorman & MacIntosh, 2015). External validity refers to when the findings of research are generalisable or applied to other samples (O’Gorman & MacIntosh, 2015). On the other hand, internal validity is about how the researchers can reasonably be sure that the independent variable or the treatment caused the lack of change or change of association (O’Gorman & MacIntosh, 2015). The validity is presented in this research through the use of many academic papers, reports, and online databases with respect to ingredient costs and nutritive values.

Regarding validity and reliability in this research, examining the source of the data has been done. The assessment refers to assessing the reputation, authority, or credibility of the source, including looking at the existence of published documents related to the data, to help with validation and for a copyright statement (Saunders et al., 2012). However, the secondary data might be biased based on certain levels (Buglear, 2012). Consequently, it is important to evaluate the precise suitability of the secondary data that may enable research to meet their research objectives partially or to answer the research questions (Saunders et al., 2012).

In achieving validity, reliability and transparency in this research, data and information from multiple trusted sources, including various documents, government publications, scientific journals, and academic literature, are the foremost references (Saunders et al., 2012). Consistent updates from market data are needed and traceable to preserve accuracy and transparency in LP modelling. Accordingly, the data presented would value validity, reliability, and transparency.

3.7 Ethical Considerations

This research honours ethical academic integrity in undertaking the research in all processes. All of the data collected has been cited properly to provide transparency. The data selection and results in this study are not bias to favour certain outcomes.

Chapter 4: Supply Chain of Livestock Feed Ingredients

In optimising diet costs, utilising SCM concept and LP in this research is instrumental. Csikai (2011) convey that regularly re-formulating diets is necessary because of the changed in quality attributes, including ingredient costs, production and modifications of products, and their nutritional values. The availability of ingredients is crucial for sustainable feed production (Wahyuni et al., 2021). However, the inconsistent reliability of global and domestic suppliers can influence ingredient availability, leading to consideration of various alternative feed ingredients in diet formulation (Irawan et al., 2022). Integrating LP and SCM in diet formulation enables feed mills to manage supply chain disruptions, maintain ingredient quality, enhance traceability and planning accuracy, reduce costs, and improve supplier performance (Irawan et al., 2022). Therefore, adopting LP and SCM is a practical approach for allocating the least-cost diet formulations.

This chapter provides a summary of the livestock ingredients' supply chain operations to help comprehend the role of LP and SCM. The chapter further outlines the supply chain activities, including the sourcing of livestock ingredients, transportation and logistics from domestic and international suppliers to WP. This chapter discusses the cost of the feed ingredients, the availability and reliability of these supply chain activities, storage and inventory in WP.

4.1 Sourcing of Livestock Ingredients, Transportation and Logistics

Many of the potential feed ingredients listed below are traded from different islands in Indonesia, but this could also imply that the source of the ingredients for WP can come from production within Indonesia or other countries. The price of goods in Jakarta (JKT), Daerah Khusus Ibukota Jakarta Province (DKI JKT), and Surabaya (SBY), East Java Province (EJ) in Java Island, as major international ports in Indonesia, may be lower than the price in WP (Herliana & Parsons, 2011; Mahasyahputra et al., 2023; Simatupang, 2013). Prices and availability of some commodities fluctuate in remote areas including Papua Island (Herliana & Parsons, 2011). Commonly, the price difference in Papua Island is twice that of Java Island (Mahasyahputra et al., 2023).

Sea transportation is the most cost-effective mode of transportation for the carriage of goods, including feed ingredients, within islands in Indonesia. Indonesia has four main ports for exporting and importing activities (Ksatrya et al., 2018). These ports are Tanjung Priok in DKI JKT, Tanjung Perak in SBY in EJ, Belawan in Medan in North Sumatra Province, and Makassar (MKS) in South Sulawesi. Goods or ingredients produced locally are also sent to WP, potentially transported to one of these major ports (Herliana & Parsons, 2011; Ksatrya et al., 2018). Transit could depend on the origin of the ingredients. Figure 10 and Figure 11 demonstrate potential shipping routes from JKT, SBY, and MKS to MKW in WP. Nonetheless, the reliance on sea transportation for the delivery of goods, the origin of ingredients, shipping schedules and geographic location can substantially make feed formulation more problematic in WP.

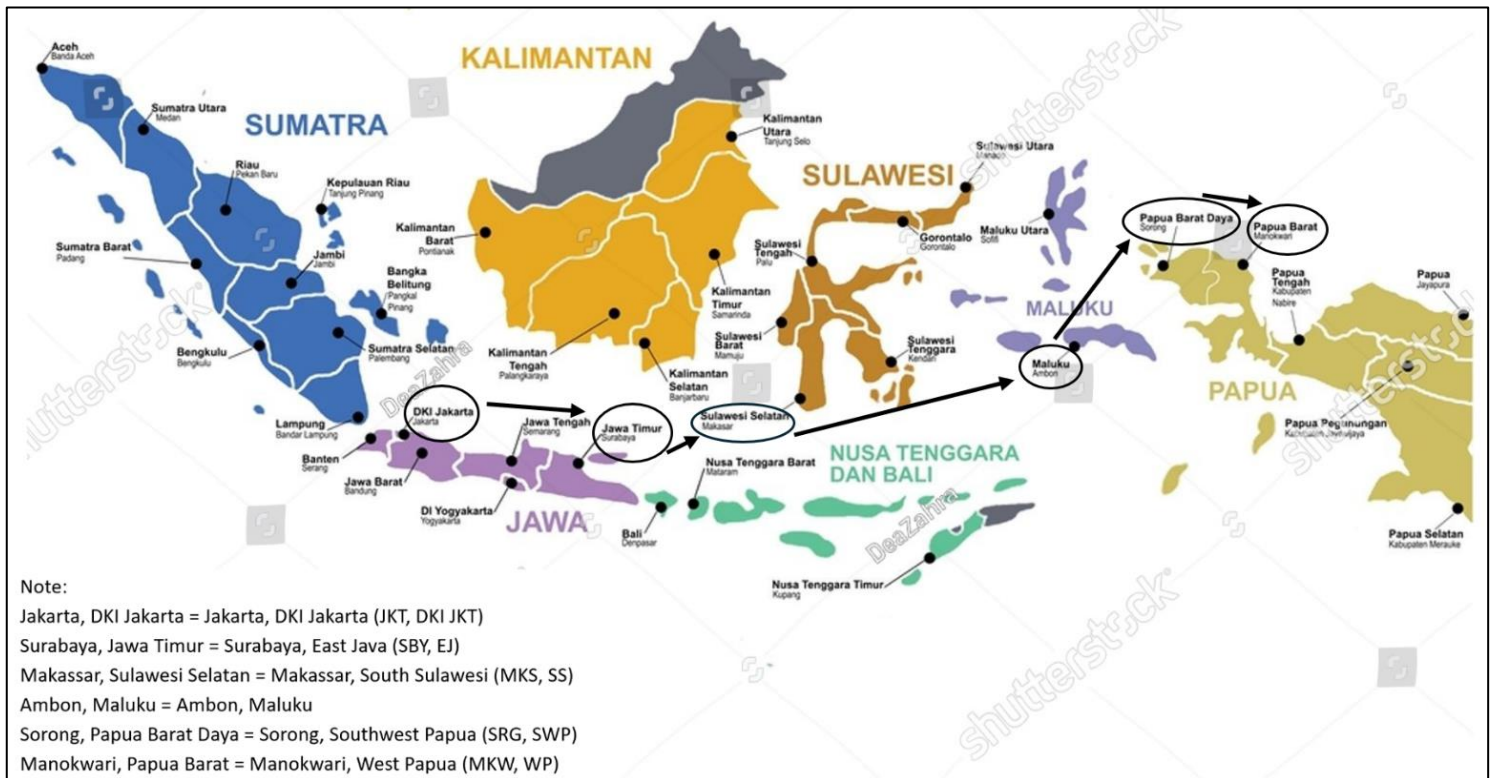


Figure 10. Shipping route to West Papua Province in Indonesia (Shutterstock, 2023).

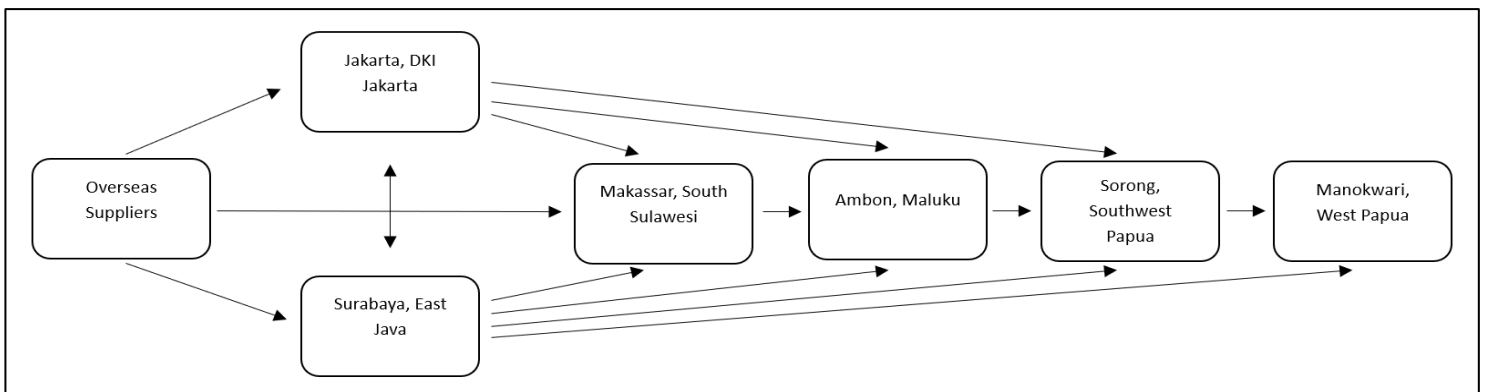


Figure 11. Shipping route to West Papua Province.

4.1.1 Maize

As the main energy source in most poultry diets, understanding the supply of maize will significantly influence the diet formulation. The price of maize in WP is Rp8,200/kg or NZD 0.86/kg (Badan Pangan Nasional, 2025), with WP producing 8,752 tons of maize in 2024 (Statistics Indonesia, 2025). Nevertheless, the production of maize in WP may not meet the demand in the province, leading to the need to trade from other regions. The seasonal production of maize is from October/November to the end of June, depending on the wet season in each region in Indonesia (Erythrina et al., 2022). Meanwhile, the price of maize in Java Island varied from Rp5,080-9,000/kg or NZD 0.53-0.94/kg (Badan Pangan Nasional, 2025). Shipping can increase the maize price in other islands (Mahasyahputra et al., 2023; Sibuea et al., 2023). Even though Indonesia imports maize from Argentina, Brazil, the USA, Ukraine, and Thailand (OEC, 2025), through Indonesian Minister of Trade Regulation (Permendag) No. 21 of 2018, Indonesia has not imported maize for feed production since 2017 (Ariyanto et al., 2023). The Indonesian government policy aims to improve the quality and production of the maize sector to reduce dependency on international trade and protect local maize farmers from global competition and international prices (Ariyanto et al., 2023). The ministry has determined six provinces for national maize production, including North Kalimantan, North Maluku, Maluku, East Nusa Tenggara, Papua, and WP, with a total of 141,000 Ha corn production areas (Ariyanto et al., 2023). Hence, with the available maize production in WP, the supply chain of maize remains reliable, yet trading maize from other islands can increase the price because of logistics and shipment.

4.1.2 Wheat

Wheat provides the nutrients necessary for poultry, and identifying the supply chain of this ingredient can affect the diet formulation. Even though Indonesia puts effort into growing wheat on various islands, there has yet to be a major production hub (Nur et al., 2018). Subsequently, Indonesia is still dependent on importing wheat (Bourgeois & Kusumaningrum, 2008; Nur et al., 2018). Countries exporting wheat to Indonesia include Australia, Argentina, Canada, Ukraine, and the USA (Anugraheni et al., 2024). Nonetheless, wheat is used as a substitute feed ingredient for maize when there is a decrease in maize production in Indonesia and an increase in global maize prices (Anugraheni et al., 2024). The price of wheat is Rp55,904/kg in JKT and SBY in Indonesia (Selina Wamucii, 2025), making the price in WP even

more expensive (Mahasyahputra et al., 2023); the price in WP is Rp111,807/kg or NZD 11.73/kg. Since Indonesia does not produce wheat, even when the prices increase, Indonesia still imports wheat from other countries due to the high demand (Anugraheni et al., 2024). However, as the wheat price increases, the wheat composition in feed ingredients should be less than maize. Ultimately, wheat is available year-round through imports from other countries, making the supply chain of wheat vulnerable to international prices in Indonesia (Bourgeois & Kusumaningrum, 2008), including WP. Thus, the wheat supply chain is unreliable to WP due to its unavailability across Indonesia and dependence on imports.

4.1.3 Rice Bran

Rice bran provides nutrients required in poultry diets, and understanding the supply chain of these ingredients can be valuable in diet formulation. The national production of rice bran for feed is located near feed mills, many of which are in West Java (WJ), DKI JKT, and EJ (White et al., 2021). With rice milling producing around eight to ten per cent rice bran (White et al., 2021), WP yields around 320kg to 400kg/acre of rice bran annually. However, when formulating diets, trading rice bran from other regions is necessary when there is a shortage of rice bran in WP. The average Indonesian price of rice bran, which could include WP, is Rp7,500/kg or NZD 0.79/kg (Kartika, 2025). In the meantime, rice bran price in JKT is low at around Rp2,300/kg or NZD 0.24/kg (Indotrading, 2025). Data show that Indonesia has imported rice bran from several countries, including Australia, Malaysia, Vietnam, and the USA (Indotrading, 2025). This import situation addresses the idea that if WP trades the rice bran from other islands, the rice bran could come from international markets. Therefore, even though the supply chain of rice bran in WP is available year-round, trading domestically and importing rice bran is necessary if shortages exist.

4.1.4 Cassava Root Meal

Identifying the supply chain of CRM is necessary as this ingredient comes from cassava plants and offers nutrients for poultry. Over 100 countries around the world produce cassava with a total output of 270 million tons (Parmar et al., 2017). Major cassava producers are Nigeria, Ghana, Northern Brazil, Thailand and Indonesia (Parmar et al., 2017). The price of CRM in Java Island is Rp3,000/kg (Indotrading, 2025). However, Indonesia imports cassava from China, Thailand, and Timor Leste when there are shortages in other islands in Indonesia (OEC, 2025). Since there is no CRM factory in WP, industries may need to trade CRM from other regions in

Indonesia. The price may increase to Rp6,000/kg or NZD 0.63/kg. Thus, although cassava can be easily found in WP, the lack of processing units negatively affects the price of CRM as it relies on inter-regional supply chain.

4.1.5 Soybean Meal

Understanding the supply chain of SBM, a crucial ingredient in completed poultry diets, is critical in optimising diet formulation. Even though Indonesia produces soybeans, SBM production remains limited (Syaranamual & Muyan, 2024; Tangendjaja, 2020). West Papua must import SBM from other regions when formulating the diets since WP has no SBM factory. Moreover, Indonesia imports SBM from Argentina, Brazil, the USA (Tangendjaja, 2020), and India (White et al., 2021). This condition means that WP also relies on imported SBM from overseas. With the SBM price in JKT or SBY at Rp7,600/kg (Indotrading, 2025), trading to WP is even more costly (Mahasyahputra et al., 2023). Since the price of goods could be double in WP than in Java Island (Mahasyahputra et al., 2023), the estimated cost of SBM in WP could be Rp15,200/kg or NZD 1.59/kg. Prices of imported goods are expected to be high due to global market volatility (Ayu, 2010). Hence, this makes the supply chain of SBM in WP unreliable due to the reliance on domestic trading, which may initially come from international markets.

4.1.6 Meat and Bone Meal

Meat and bone meal contain nutrients needed for a poultry diet; identifying the supply chain of these ingredients is helpful in diet formulation. While Indonesia produces limited MBM (Yanuartono et al., 2020), data reveal that Indonesia imports this ingredient from the USA, New Zealand and Canada in 2023 (OEC, 2025). This condition also means that the MBM trading to WP potentially comes from domestic productions and from overseas. The price of MBM is Rp8,800/kg in JKT and SBY (Indotrading, 2025). Nonetheless, due to the additional cost of transportation to WP (Mahasyahputra et al., 2023), the price can reach Rp17,600/kg or NZD 1.78/kg. Therefore, the supply chain of MBM to WP relies on trading from other islands in Indonesia, which makes the supply chain in WP vulnerable and subject to international market volatility.

4.1.7 Fish Meal

Gaining insights into the supply chain of fish meal, an ingredient component in poultry feed, can influence diet formulation. Indonesia produces around 60,000 tons of fish meal annually, mainly in the feed industry in JKT and SBY (Luhur et al., 2021). Meanwhile, the average demand for FM for feeds is approximately 130,000 tons per year (Luhur et al., 2021). Despite this, Indonesia still imports FM from global markets to meet the national demand, including from the USA, South Korea, Thailand, Vietnam, Peru, and Chile (Luhur et al., 2021). The price of FM in Java Island is Rp8,500/kg (Indotrading, 2025). Conversely, the transportation cost leads to double price to WP (Mahasyahputra et al., 2023), at Rp17,000/kg or NZD 1.78/kg. Consequently, the supply of FM in WP for use in diet formulation is available year-round; however, reliance on domestic trading and international suppliers makes the supply chain of fish meal to WP unreliable.

4.1.8 Copra Meal

Due to the CM nutrient profile provided in this research diet, the supply chain of CM is necessary to maximise the diet formulation. Indonesia is one of the top copra meal exporters in the world, along with the Philippines and Sri Lanka (Punzalan & Rosentrater, 2024). Many provinces in Java, Sumatra, Sulawesi, and Maluku islands are central to coconut production (MAI, 2022), with prices ranging from Rp12,279-23,7389/kg in JKT and SBY (Selina Wamucii, 2025). While copra meal production is expected to reach 540,000 tons, domestic consumption in the feed industry is expected to reach 265,000 tons by 2023/2024 (Meliyana, 2023). However, countries exporting copra meal to Indonesia are Timor-Leste, Thailand, and Malaysia (OEC, 2025). The import of copra meal might occur when the production of copra meal is low in Indonesia. In WP, copra meal production is limited, with prices ranging from Rp3,000-5,000/kg or NZD 0.31-0.52/kg (Killian et al., 2022). Since the copra meal production in WP is limited (Killian et al., 2022), WP needs to trade with other regions if there is a shortage of copra in formulating the diets. Therefore, even though the production of copra meal is available in WP, the supply chain of this ingredient is relatively reliable from other regions of Indonesia; to meet further demand, importing from other countries might be necessary.

4.1.9 Black Soldier Fly Larvae

Black soldier fly larvae provide proteins, fats, amino acids, vitamins, and minerals that can be utilised in diet formulations; understanding the supply chain of BSFL affects formulations. Many countries have established BSFL farming as a sustainable alternative feed ingredient across different continents in Asia, Africa, and Latin America (Barragán-Fonseca et al., 2024). Brazil, Chile, and Costa Rica are the leaders in the legislation, production, and exportation of insect meal, frass, oil, eggs, larvae, and other products using black soldier fly (Barragán-Fonseca et al., 2024). In Southeast Asia, countries like Vietnam, Malaysia, Singapore, and Indonesia produce BSFL for animal feed and waste management (Barragán-Fonseca et al., 2024). Some literature has suggested that Indonesia produced BSFL (Khasanah et al., 2024; Putra et al., 2023). However, as Barragán-Fonseca et al. (2024) stated in their paper, many medium-scale businesses produce insects for local demands, and this is also applied in Indonesia. The price of BSFL in Java Island is Rp39,500/kg (Tokopedia, 2025). Even though WP has the same opportunity to establish the BSFL farming, WP needs to import this ingredient, if needed for animal feed, from other regions in Indonesia. Consistently, like other ingredients, if BSFL is delivered to WP, the price increases twice the price of Java Island (Mahasyahputra et al., 2023) at Rp79,000/kg or NZD 8.29/kg. Thus, the BSFL production is available in Indonesia; however, the supply chain of BSFL specifically to WP is unreliable.

4.1.10 Cassava Leaf Meal

One plant source for protein, vitamins and minerals can be derived from cassava leaves (Diarra & Devi, 2015; Glatz, 2017); the supply chain of CLM may influence the outcome in diet formulation. Countries like Nigeria, Ghana, Northern Brazil, Thailand and Indonesia are major cassava producers in the world (Parmar et al., 2017). Thailand and Indonesia have developed further products, including CLM. Cassava is grown abundantly in WP all year round (MAI, 2023), which also means that cassava leaves are widely available in the region. However, since the CLM is unavailable as a feed ingredient in WP, feed producers need to import CLM from other regions in Indonesia if it is incorporated in the chicken diets. The price of 1kg of CLM is Rp35,000 (Tokopedia, 2025) in Java Island, which, if traded to WP, the price rises twice (Mahasyahputra et al., 2023) to Rp70,000/kg or NZD 7.35/kg. Cassava leaf meal has so much potential in WP due to the fact that this ingredient is available in its natural form; however, due to the unavailability of CLM production in WP, the supply chain of CLM is unreliable.

4.1.11 Palm Oil

Palm oil acts as another key source of energy utilised in poultry diets (Long et al., 2019); it is critical to help comprehend the PO's supply chain to WP. Indonesia is the largest producer and exporter of PO in the world (Khatiwada et al., 2021), with values for 35,000,000 mt (Rival, 2018). Other countries producing PO include Malaysia, Thailand, and Colombia (Rival, 2018). Regions like Riau Province, Centre Kalimantan, and West Kalimantan are the top three largest producers, covering 3,401.6, 2,171 and 2,133.4 (thousand ha) of the planted area of oil palm, respectively, in 2023 (Statistics Indonesia, 2025). Although the production of PO is lower than other regions, WP covered 76 thousand ha for this plant, with the price of PO in WP being at Rp15,945/litre or NZD 1.67/litre (Badan Pangan Nasional, 2025). West Papua produces PO and trades it to other provinces in Indonesia (Hutabarat, 2024). Considering the abundance of PO in the country and the availability in WP, this ingredient is one of the most reliable supply chains to WP.

4.1.12 Limestone

Limestone is used for its calcium content, and comprehending this ingredient supply chain could impact dietary formulation. This abundant mineral resource is found across Indonesia, including in Sumatra, Sulawesi, Java, Nusa Tenggara, and Papua Islands (Lukman et al., 2020). Since Indonesia produces limestone, the price is around Rp265/kg (Indotrading, 2025). Nonetheless, if needed for feed ingredients, WP needs to import from other islands due to no limestone factory established for feed formulation in WP. Nevertheless, OEC (2025) stated that Indonesia sourced limestone from Vietnam, Malaysia, and the Philippines. This import may happen when there is a shortage of limestone in a certain period of time. Likewise, trading limestone from other regions in Indonesia to WP may involve sourcing the ingredient from different countries. Consequently, the price of limestone doubled to WP (Mahasyahputra et al., 2023) at Rp530/kg or NZD 0.06/kg. Therefore, the supply chain of limestone for feed ingredients in WP remains unreliable, subject to the availability of limestone in other regions in Indonesia.

4.1.13 Dicalcium Phosphate and Tricalcium Phosphate

Ingredients that can be useful as a source of calcium and phosphorus are dicalcium phosphate and tricalcium phosphate; the supply chain of these ingredients may be insightful for formulating poultry diets. The total production of DCP for animal feed is around 4,000,000 tons per year (Toama, 2017). The leading producers of calcium phosphates, including DCP and TCP, were Jordan, Morocco and Peru in 2023 (OEC, 2025). Indonesia, on the other hand, was one of the top three importers of calcium phosphates in 2023. Jordan, Egypt, Algeria, and Peru have reported exporting calcium phosphate to Indonesia (OEC, 2025). Indonesia, including WP, does not produce these calcium phosphates; the price of DCP is at Rp12,000/kg in JKT (Tokopedia, 2025), and the price of TCP is Rp34,000/kg in JKT and SBY (Indotrading, 2025). The price of these ingredients can be increased in WP by double the price due to the transportation and distribution cost (Mahasyahputra et al., 2023), which can be at Rp24,000/kg or NZD 2.52/kg DCP and Rp68,000/kg or NZD 7.35/kg TCP. The reliance on trading from other regions, makes the supply chain of this ingredient to WP unreliable, subject to the price in other islands in Indonesia and fluctuations in the global market.

4.1.14 Lysine, DL-Methionine, and L-Threonine

Lysine, dl-methionine, and l-threonine are included in poultry diets, acknowledging that the supply chain of these ingredients is valuable in formulating diets. Reports show that some companies in Indonesia produce lysine, dl-methionine, and l-threonine. Ihwah and Syafira (2021) mentioned that a company located in EJ in Indonesia has produced and exported l-lysine as an animal feed product to several countries. Similarly, Rachmawati et al. (2023) found that Indonesia has produced methionine located in EJ. On the other hand, no factory in WP produces these ingredients, which leads to a dependence on suppliers in other regions. Nonetheless, Indonesia still imports lysine from China, South Korea and France in 2023 (OEC, 2025), methionine from Singapore, China, and Japan (OEC, 2025) and other amino acids from China, Switzerland, and Germany in 2023 (OEC, 2025). This also means WP could get these ingredients from other islands and countries. Based on Indotrading (2025), the amino acids are available in other islands in Indonesia with prices of Rp29,000/kg lysine, Rp56,200/kg dl-Methionine and Rp40,000/kg l-threonine. The prices of these ingredients in WP are then expected to double from Java Island due to distribution and transportation costs (Mahasyahputra et al., 2023), which could reach Rp58,000/kg or NZD 6.09/kg, Rp112,400/kg

or NZD 11.79/kg, and Rp80,000/kg or NZD 8.39/kg for each of lysine, DL-methionine, and L-threonine, correspondingly. Hence, the reliance on supplying from other regions, which may initially come from overseas, makes the supply chain of these ingredients unreliable to WP.

4.1.15 Sodium Chloride and Sodium Carbonate

Sodium chloride provides sodium and chloride in poultry diets, grasping into its supply chain is beneficial in interpreting the dietary formulation. Various provinces in Indonesia produce salt, including WJ, EJ, Central Java, West Nusa Tenggara, East Nusa Tenggara, and South Sulawesi (Sunoko et al., 2023). Meanwhile, WP is in the top 15 main salt markets that do not produce salt in the region (Sunoko et al., 2023). Despite the production of salt reaching 2.5 million tons in 2020, Indonesia still needs around 4.4 million tons of salt, which requires imports from other countries to meet the national demand (Sunoko et al., 2023). Countries exporting salt to Indonesia are from Australia, India, and New Zealand (OEC, 2025). Salt price in Java Island was Rp3,800/kg (Indotrading, 2025). In the meantime, due to the transportation, the cost of salt for animal feeds doubled (Mahasyahputra et al., 2023), at Rp7,600/kg or NZD 0.8/kg. Due to the high demand and low production of salt in Indonesia, the supply chain of this ingredient to WP is vulnerable—the reliance on domestic trading and international suppliers further complicated WP's supply chain.

Alternatively, since sodium carbonate has been promoted into the poultry diets, familiarising oneself with sodium carbonate in the feed and its supply chain helps formulate a diet. Arfah and Suksmana (2021) and Wareza (2021) reported that Indonesia imports all the required sodium carbonate, including WP. Sutriyanto (2021) stated that Indonesia can import around one million tons of sodium carbonate. The United States Environmental Protection Agency (2023) confirmed that the USA has exported 821 million kg of sodium carbonate to Indonesia. Other countries that import are Germany, China, and India (Volva, 2024). Currently, the sodium carbonate price in JKT is Rp4,500/kg (Indotrading, 2025). Meanwhile, WP's price can double the cost in Java Island due to transportation costs (Mahasyahputra et al., 2023), which can lead to Rp9,000/kg or NZD 0.94/kg. Thus, the supply chain of this ingredient to WP could be more reliable due to the reliance on imports, which makes WP vulnerable to price fluctuations in Indonesia or the global market.

4.1.16 Mineral and Vitamin Premixes

The beneficial contents of mineral and vitamin premixes are substantial, comprehending the premixes supply chain can be resourceful in formulating a diet. Many companies in Indonesia produce and distribute mineral and vitamin premixes located mainly on Java Island, such as Berdikari Veterinary Animal Health Care (Berdikari Veterinary Animal Health Care, 2024), Fenanza (Fenanza, 2021), Medion Farma (Medion Farma, 2024) and Zagro (Zagro, 2024). Meanwhile, there are no mineral and vitamin factories in WP. Although Indonesia has many companies that produce and distribute these premixes, data shows that Indonesia imports the mineral and vitamin premixes from China and Malaysia (Volva, 2024). According to Indotrading (2025), in JKT, mineral premix costs Rp17,188/kg, while vitamin premix costs Rp7,956/kg. Conversely, in WP, the price could rise twice that of Java Island due to the transportation cost (Mahasyahputra et al., 2023), which could be Rp34,236/kg or NZD 3.59/kg and Rp15,912/kg or NZD 1.67/kg for mineral and vitamin premixes, respectively. Thus, the supply chain for these premixes in WP is unreliable since WP relies on trading from other regions, which may involve sourcing from overseas.

4.2 Storage and Inventory

After all livestock feed ingredients arrive in WP, storage and inventory management become crucial for maintaining their quality. When delivering feed ingredients to storage, a temperature-controlled technology is necessary. Many goods must be kept at specific temperatures or conditions and protected from toxic materials (Khan & Yu, 2019), including during transfer to and within the warehouses. The care of feed ingredients should be based on their specific needs. When the goods arrive at the warehouses, data about their arrival, shelf life, and related information must be recorded (Khan & Yu, 2019). This process is vital to address potential issues like shortages or scarcity of ingredients when needed (Aminuddin & Okdinawati, 2023). Alongside the care and maintenance of the warehouse, the storage and inventory system must meet safety requirements for both the ingredients and personnel handling them, ensuring overall safety (Khan & Yu, 2019). Moreover, as suggested by Khan and Yu (2019), and Simatupang (2013), regular monitoring of storage, inventory, stock rotation, and maintenance should be undertaken to identify and resolve potential issues. Thus, effective warehouse management, including storage and inventory processes, can

improve the supply chain of feed ingredients and help maintain the quality of the selected feed ingredients.

4.3 Conclusion

In summary, WP's supply chain faces many difficulties due to its reliance on imported and domestically traded commodities. Due to this dependence, WP is vulnerable to price changes from domestic trade within Indonesia and internationally. Some aspects that can disrupt the supply chain include limited locally grown ingredients, delayed transportation, and the high costs of transportation and logistics. Moreover, improved storage and inventory management are needed to enhance year-round ingredient feed quality and supply. Finally, examining the sourcing of livestock ingredients, transportation, logistics, storage and inventory management can provide valuable insight into the SCM and diet formulation in WP.

Chapter 5: Results

This chapter exhibits the research results and examines the findings regarding the integration of ingredient nutrient composition values for feed ingredients, LP modelling, and the supply chain of these ingredients. The data presented in this study are the results and analysis of the formulated LP modelling for the optimisation of feed cost for 25 different poultry diets. The chapter offers a comprehensive overview of all the results of the optimal solution obtained using LP modelling.

The results of the formulated diets are divided into three groups. The first group includes five diet formulations for broilers based on nutritional specifications for as-hatched broilers, targeting a live weight of over 3.5 kg (>7.7 lb) across five stages from starter to finisher. The second group comprises ten diet formulations for layers, based on rearing and production period nutritional recommendations for Hy-Line Brown max layers, aimed at optimal economic performance from starter to layer at the lower limit of energy requirements. The third group also consists of ten diet formulations for layers, following similar rearing and production period nutritional guidelines for Hy-Line Brown max layers, but targeting the upper limit of energy requirements across ten stages from starter to layer. All formulated diets meet all nutritional requirements and constraints, including considerations for cost and nutrient levels of feed ingredients, combining imported, inter-island, and locally produced ingredients.

5.1 Broiler Diet Formulations Results

Five broiler diets have been designed for different stages, including starter, grower, finisher 1, finisher 2, and finisher 3. The summary of broiler diets formulated by LP modelling is shown in Table 7. The cost of these diets decreases as the broilers grow older. The feed cost ranged from NZD 1.49 per kg during the starter stage to NZD 1.15 per kg at the finisher stage. In all the diets, maize consistently remains the main ingredient, constituting between 50.88% and 54.65% of the total formulation. Soybean meal is the second most common ingredient, making up between 27.61% to 28.77%. The inclusion level of FM decreases as the birds reach the later stages, dropping from 6.39% to 0.34%. Similarly, BSFL was only used in the starter stage at 3.71% and is absent in the later stages. Meanwhile, PO inclusion increases from 2.39% to stabilise at 6% through the last two finisher stages. Limestone, sodium chloride, sodium carbonate, synthetic amino acids, minerals, and vitamins are included in small amounts across

all diets, ranging from 0.01% to 2.13%. Of these five formulations, the finisher 3 diet is the least costly, maximising 16 different ingredients at NZD 1.15 per kg.

Table 7
Broiler Diet Formulations

Ingredients (%)	Broiler Stage				
	Starter	Grower	Finisher 1	Finisher 2	Finisher 3
Maize	51.17	54.08	52.84	54.65	50.88
CRM	-	-	-	-	5.98
SBM	30	30	30	27.61	28.77
FM	6.39	3.45	2.26	1.48	0.34
CM	1.52	2.95	4.15	6.23	4.13
BSFL	3.71	1.73	-	-	-
PO	2.39	3.92	5.82	6	6
LiSt	1.96	1.1	2.13	1.2	1.1
L-Lys	0.17	0.18	0.16	0.18	0.14
DL-Met	0.19	0.2	0.2	0.18	0.17
L-Thre	0.12	0.11	0.09	0.09	0.07
NaCl	0.37	-	0.36	0.38	0.4
Na ₂ CO ₃	-	0.29	-	-	0.01
MP	1	1	1	1	1
VP	1	1	1	1	1
Cost (NZD/kg)	1.49	1.33	1.19	1.16	1.15

The nutritive values of broiler diet formulations are shown in Table 8. The dry matter remained relatively stable at around 891 g/kg across all stages. Declining trends were observed in various nutrient profiles throughout the broiler diet stages. The CP content decreased from 243 g/kg at the starter stage to 188 g/kg at the finisher 3 stage. Similarly, ash content reduced from 43 g/kg to 30 g/kg. Available phosphorus showed a similar decreasing trend, dropping from 5 g/kg in the starter to 3.2 g/kg in the finisher 3 stage. All essential and non-essential amino acids also gradually dropped at each broiler stage. Although fat content increased from 60 g/kg at the starter stage to 88 g/kg in Finisher 2, it slightly declined to 86 g/kg in Finisher 3. Calcium content fluctuated from 13 g/kg in the starter stage then hit the peak at 10.2 g/kg at the finisher 1 stage and declined to 5.5 g/kg in the finisher 3 stage. Conversely, starch depicted an inclined trend from 333 g/kg in the starter stage to finishing at 375 g/kg in the final stage. AMEn showed the exact same set of values for broiler requirement, rising from 12.4 MJ/kg in the starter diet to 13.2 MJ/kg in the finisher 3. Overall, all broiler diets met the nutrient requirements. More information on each stage of the broiler diets is available from Appendix 1 to 5.

Table 8
Nutritive Values of Broiler Diet Formulations

Nutrient Profile	Unit	Broiler Stage				
		Starter	Grower	Finisher 1	Finisher 2	Finisher 3
DM	g/kg	891	891	893	892	891
Ash	g/kg	43	37	33	32	30
GE	MJ/kg	17	17	17	18	17
CP	g/kg	243	220	206	196	188
Fat	g/kg	60	71	87	88	86
Starch	g/kg	333	352	344	356	375
NDF	g/kg	106	111	112	122	111
ADF	g/kg	45	46	47	50	47
Ca	g/kg	13	7.5	10.2	6.2	5.5
Mg	g/kg	2.1	1.8	2	1.8	1.7
K	g/kg	9	9	9	9	9
Na	g/kg	2.3	1.8	1.8	1.8	1.8
AvP	g/kg	5	4.2	3.8	3.6	3.2
AMEn	MJ/kg	12.4	12.8	13	13.1	13.2
Arg	g/kg	14	13	12.5	11.9	11.5
His	g/kg	5.4	5	4.7	4.5	4.4
Iso	g/kg	8.9	8	7.5	7.1	6.9
Leu	g/kg	17.2	15.9	15	14.4	13.8
Lys	g/kg	13.2	11.8	10.8	10.2	9.6
Met	g/kg	5.5	5.1	4.8	4.5	4.2
Phe	g/kg	10	9.3	8.8	8.4	8.2
Thr	g/kg	8.8	7.9	7.2	6.8	6.4
Val	g/kg	10.1	9.1	8.4	8	7.7
Ala	g/kg	11.5	10.2	9.3	8.8	8.3
Asp	g/kg	13.8	12.5	11.6	11	10.7
Cys	g/kg	2.7	2.6	2.5	2.4	2.4
Glu	g/kg	19.7	18.2	17.1	16.4	15.9
Gly	g/kg	10.8	9.2	8.3	7.8	7.2
Pro	g/kg	12.2	11.2	10.4	9.9	9.6
Ser	g/kg	11	10.1	9.5	9	8.7
Tyr	g/kg	7.8	6.9	6.2	5.9	5.7

5.2 Layer Diet Formulations at the Lower Limit Energy Requirements

Results

A ten-layer diet formulation at the lower limit of energy needs was developed at different stages of the layers, from starter 1, grower, developer, pre-lay, peaking, to layer 5, using LP modelling. A summary of the layer diets created by LP modelling is shown in Table 9. The feed cost ranged from NZD 0.89 per kg to NZD 1.79 per kg across various diets. Maize was incorporated in the early stages of broilers from 5.56% to 16.23% inclusion until the pre-lay stage and consistently served as the main ingredient when hitting the peak stage until the later stages, making up 59.01% to 61.78% of the total formulations. Cassava root meal was used in the early stages as the primary ingredient steadily at 40% before being reduced to zero in later stages after pre-lay and reincorporated at 3.35% at the last stage. Soybean meal was one of the most used ingredients, comprising between 12.11% (at peaking) and 29.9% (at starter 1). Copra meal usage ranged from 9.77 g/kg in starter 1 to 20 g/kg in developer, then decreased to zero in the peaking, layer 2, and layer 3 stages, with a slight usage at 0.93 g/kg in layer 4 and 0.73 in layer 5. The inclusion of BSFL occurred only in peaking stage at 10.4% and declined to layer 2 and layer 3 stages at 5.39% and 3.11% respectively. Both PO and limestone were included in all formulations, with PO varying from 2.28% (developed stages) to 5% in most diets. Limestone showed a rising trend from 1.19% in starter 1 to 9.76%. Synthetic amino acids were added in small amounts, just under 1%, while mineral and vitamin premixes remained steady at 1% across all formulations. Among these ten options, the developer diet was the most affordable, utilising 15 different ingredients at NZD 0.89 per kg.

Table 9
 Layer Diet Formulations at the Lower Limit Energy Requirement

Ingredients (%)	Layer Stage									
	Starter 1	Starter 2	Grower	Developer	Pre-Lay	Peaking	Layer 2	Layer 3	Layer 4	Layer 5
Maize	5.56	6.62	6.35	16.23	6.78	59.01	61.7	61.69	61.78	59.82
CRM	40	40	40	40	40	-	-	-	-	3.25
SBM	29.9	23.54	20.18	13.19	16.65	12.11	13.94	16.4	17.07	15.99
FM	6.08	5.86	5.34	4.53	6.07	4.12	3.62	2.64	3.4	3.12
CM	9.77	15.27	19.63	20	19.54	-	-	-	0.93	0.73
BSFL	-	-	-	-	-	10.4	5.39	3.11	-	-
PO	5	5	5	2.28	5	5	5	5	5	5
LiSt	1.19	1.25	1.07	1.49	3.64	7.04	8.06	8.85	9.49	9.76
L-Lys	0.06	0.06	0.05	0.001	0.0006	-	-	-	-	-
DL-Met	0.2	0.16	0.15	0.07	0.12	0.12	0.11	0.11	0.11	0.1
L-Thre	0.06	0.05	0.04	-	0.03	0.003	0.004	0.005	-	0.005
NaCl	0.19	0.18	0.19	0.21	0.17	-	-	-	0.22	0.23
Na ₂ CO ₃	-	-	-	-	-	0.2	0.18	0.21	-	-
MP	1	1	1	1	1	1	1	1	1	1
VP	1	1	1	1	1	1	1	1	1	1
Cost (NZD/kg)	1.1	1.03	0.99	0.89	0.94	1.79	1.42	1.25	1.02	1

The nutritive values of the layer lower limit energy diet formulations in this research are shown in Table 10. The dry matter remained relatively stable, fluctuating from 888 g/kg to 901 g/kg across all stages. Crude protein (CP) declined steadily from 214 g/kg in the starter 1 stage to 142 g/kg in the layer 5 stage. Conversely, starch increased gradually from 333 g/kg in the starter stage to 412 g/kg in the layer 5 stage. Similarly, calcium gradually rose from 9 g/kg in the early stages to a significant jump to 39.2 g/kg in the layer 5 stage. An increased trend occurred for fat content from 67 g/kg in starter 1 stage and hit the peak at 90 g/kg in peaking stage and a slight gradual drop at 79 g/kg in the final stage. Apparent metabolisable energy fluctuated followed the identical values of the nutrient requirements, from 11.3 MJ/kg in the developer stage to 12.6 MJ/kg in both layer 4 and 5 stages. Additionally, available phosphorus and some essential amino acids such as lysine, methionine, and threonine showed fluctuating patterns; they reached lower levels in the final stage compared to the starter stage. More information on each stage of these layer lower limit energy diets is available from Appendix 6 to 15.

Table 10
Nutrient Profile of Layer Diet Formulations at the Lower Limit Energy Requirement

Nutrient Profile	Unit	Layer Stage									
		Starter 1	Starter 2	Grower	Developer	Pre-Lay	Peaking	Layer 2	Layer 3	Layer 4	Layer 5
DM	g/kg	892	892	891	888	894	901	900	899	899	899
Ash	g/kg	50	49	49	45	48	35	30	27	26	25
GE	MJ/kg	17	17	17	16	16	17	16	16	16	16
CP	g/kg	214	195	185	155	173	181	162	156	149	142
Fat	g/kg	67	67	66	40	66	90	85	82	80	79
Starch	g/kg	333	339	337	400	340	383	400	400	401	412
NDF	g/kg	107	129	146	150	142	100	94	91	90	87
ADF	g/kg	59	68	75	74	73	39	35	34	33	32
Ca	g/kg	9	9	8	9	18	33.3	35	36.7	38.3	39.2
Mg	g/kg	1.9	1.9	1.9	1.9	2.4	2.8	2.9	3.1	3.1	3.2
K	g/kg	12.4	12.5	12.8	11.7	12.1	5.7	5.7	5.9	6	5.9
Na	g/kg	1.5	1.5	1.5	1.5	1.5	1.6	1.4	1.4	1.4	1.4
AvP	g/kg	4.5	4.4	4.3	3.9	4.3	3.8	3.5	3.3	3.4	3.2
AMEn	MJ/kg	12.13	11.92	11.72	11.3	11.51	13.2	13	12.8	12.6	12.6
Arg	g/kg	13.3	12.3	11.9	9.9	11.1	9.2	8.6	8.6	8.5	8
His	g/kg	4.5	4	3.7	3	3.4	4	3.7	3.7	3.6	3.4
Iso	g/kg	7.5	6.6	6.1	4.9	5.6	6.6	5.9	5.7	5.4	5.1
Leu	g/kg	13.1	11.7	10.9	9.4	10.1	13.5	12.5	12.2	11.8	11.2
Lys	g/kg	10.7	9.2	8.2	6	7.2	8.3	7.4	7.1	6.8	6.4
Met	g/kg	4.8	4.2	3.9	2.8	3.5	4.2	3.7	3.5	3.4	3.2
Phe	g/kg	8.5	7.6	7.1	5.8	6.5	7.2	6.7	6.6	6.4	6
Thr	g/kg	6.9	6.0	5.5	4.1	5	5.8	5.2	5	4.7	4.5
Val	g/kg	8.3	7.6	7.1	6	6.6	8.1	7.1	6.7	6.2	5.9
Ala	g/kg	8.5	7.7	7.1	6.2	6.8	9.9	8.7	8.2	7.7	7.3
Asp	g/kg	11.8	10.4	9.7	7.9	8.9	10.6	9.2	8.8	8.1	7.7
Cys	g/kg	2.1	1.8	1.7	1.5	1.5	1.9	1.9	1.9	2	1.9
Glu	g/kg	18.1	16.7	16.1	13.4	14.9	14.4	12.8	12.5	11.8	11.2
Gly	g/kg	8.6	7.7	7.2	6.1	6.9	8.7	7.7	7.1	6.9	6.5
Pro	g/kg	8.7	7.6	6.9	5.9	6.4	10.1	9.2	8.9	8.4	8
Ser	g/kg	9.2	8	7.4	6	6.8	7.9	7.3	7.2	7	6.6
Tyr	g/kg	6	5.2	4.7	3.8	4.3	6.8	5.7	5.2	4.6	4.4

5.3 Layer Diet Formulations at the Upper Limit Energy Requirements

Results

A ten-layer diet formulation at the upper limit requirement has been generated at different stages of layers from starter 1, grower, developer, pre-lay, peaking, and layer 5. The summary of layer diets formulated by LP modelling is depicted in Table 11. The feed cost varied from NZD 0.97 per kg to more than double at NZD 2.57 per kg in different stages. In most layer diets, maize serves as one of the main ingredients, from 15.27% to 66% in all the total formulations. Cassava root meal acted as the most used ingredients only in early stages of layers ranging from 38.39% to 40%, then dropped at 12.7% to 14.76% in developer and pre-lay stages before completely zero inclusion from peaking stage to the final stages. However, SBM consistently comes as the one of the frequently used ingredients, comprising as little as 0.68% to 30% usage in all layer formulations. Meat and bone meal were included in the diets at peaking and layer 2 stages at 2.27% and 0.37% respectively. Fish meal incorporated ranged from 3.03% to 7.29% across all layer diets. Copra meal was used from 0.02% to 15.83% in the developer stage, then dropped to 10.24% in the pre-lay stage, and then fell to zero from the peaking stage to the layer 5 stage. Limestone usage started at 1.06% then a slight decline in the grower stage at 0.94% and increased gradually to reach 8.96% at the final stage. Some synthetic amino acids, sodium chloride and sodium carbonate were used in a minor portion, starting from 0.005% to 0.19%. Palm oil, mineral and vitamin premixes were used constantly in all layer diets at 5%, 1%, and 1%, correspondingly. Among these ten formulations, the developer diet is the least-cost diet, maximising 16 different ingredients at NZD 0.97 per kg.

Table 11
Layer Diet Formulations at the Upper Limit Energy Requirement

Ingredients (%)	Layer Stage									
	Starter 1	Starter 2	Grower	Developer	Pre-Lay	Peaking	Layer 2	Layer 3	Layer 4	Layer 5
Maize	15.82	15.27	16.83	46.42	40.97	59.24	63.32	64.09	64.61	66
CRM	38.39	40	38.07	12.7	16.63	-	-	-	-	-
SBM	30	23.8	20.25	12.35	14.76	0.68	2.53	4.68	7.05	6.07
MBM	-	-	-	-	-	2.27	0.37	-	-	-
FM	7.29	7.16	6.52	4.06	6.43	3.56	5.32	4.59	4.06	3.03
CM	0.02	5.32	10.04	15.83	10.24	-	-	-	-	-
BSFL	-	-	-	-	-	21.48	14.14	11.62	8.42	8.65
PO	5	5	5	5	5	5	5	5	5	5
LiSt	1.06	1.1	0.94	1.39	3.7	5.42	6.91	7.8	8.6	8.96
L-Lys	0.01	0.005	-	-	-	-	-	0.01	0.02	0.04
DL-Met	0.19	0.15	0.14	0.05	0.1	0.21	0.3	0.07	0.08	0.08
L-Thre	0.05	0.04	0.03	-	0.01	-	-	-	-	-
NaCl	0.17	0.16	0.17	-	0.17	-	-	-	-	-
Na ₂ CO ₃	-	-	-	0.2	-	0.14	0.11	0.14	0.16	0.18
MP	1	1	1	1	1	1	1	1	1	1
VP	1	1	1	1	1	1	1	1	1	1
Cost (NZD/kg)	1.15	1.08	1.03	0.97	1.01	2.57	2.03	1.82	1.59	1.59

The nutritive values of layer diets at the upper limit energy requirement, formulated by LP modelling, is shown in Table 12. The dry matter ranged from 891-894 g/kg for the first five stages, then increased to 904 g/kg at the peaking stage and slightly decreased to 902 g/kg at the layer 5 stage. In the starter 1 stage, AMEn began at 12.97 MJ/kg, dipped slightly to 12.55 MJ/kg during the grower, developer, and pre-lay phases, then rose sharply to a peak of 13.8 MJ/kg, before gradually decreasing and stabilising at 13.2 MJ/kg in the final two stages. The values of all stages of AMEn followed the corresponding values of nutrient requirements. Available phosphorus fluctuated, beginning at 4.5 g/kg, declining to 3.9 g/kg from starter 1 through developer, peaking at 4.8 g/kg in the peak stage, then gradually falling to 3.2 g/kg in layer 5. Calcium was steady at 8-9 g/kg from the starter 1 to the developer stage, then increased notably in the pre-lay stage to 18 g/kg, continued to rise significantly in peaking stage at 33.3 g/kg and gradually increased to 39.2 g/kg in layer 5. While starch content showed fluctuations, it increased from 387 g/kg in starter 1 to 428 g/kg by the later stages. Meanwhile, fat content started at 71g/kg at the early stage and hit the top at the peak stage at 101 g/kg and drop slowly to 88 g/kg in the last two stages. Crude protein (CP) decreased from 207 g/kg in starter 1 to 142 g/kg in layer 5. Although all amino acids fluctuated, they showed a decreasing trend, with lysine dropping from 10.7 g/kg to 6.4 g/kg, methionine from 4.8 g/kg to 3.2 g/kg, and threonine from 6.9 g/kg to 4.5 g/kg across the stages. Further details on each stage of these upper limit energy diets are provided from Appendix 19 to 28.

Table 12

Nutrient Profile of Layer Diet Formulations at the Upper Limit Energy Requirement

Nutrient Profile	Unit	Layer Stage									
		Starter 1	Starter 2	Grower	Developer	Pre-Lay	Peaking	Layer 2	Layer 3	Layer 4	Layer 5
DM	g/kg	892	892	891	891	894	904	902	902	901	902
Ash	g/kg	46	46	45	36	39	47	37	33	30	28
GE	MJ/kg	17	17	17	17	17	17	17	16	16	16
CP	g/kg	207	189	179	155	166	193	169	159	151	142
Fat	g/kg	71	70	70	76	76	101	95	92	88	88
Starch	g/kg	387	395	390	395	388	385	411	415	419	428
NDF	g/kg	68	88	108	149	119	111	101	99	95	96
ADF	g/kg	39	47	56	64	52	44	38	37	35	35
Ca	g/kg	9	9	8	8	18	33.3	35	36.7	38.3	39.2
Mg	g/kg	1.7	1.7	1.7	1.7	2.2	2.6	2.7	2.9	3	3
K	g/kg	10.4	10.5	10.7	9.2	8.7	4.5	4.4	4.5	4.7	4.5
Na	g/kg	1.5	1.5	1.5	1.5	1.5	1.6	1.4	1.4	1.4	1.4
AvP	g/kg	4.5	4.4	4.3	3.9	4.3	4.8	4.1	3.7	3.5	3.2
AMEn	MJ/kg	12.97	12.76	12.55	12.55	12.55	13.8	13.6	13.4	13.2	13.2
Arg	g/kg	12.2	11.2	10.8	9.6	9.8	8.6	7.7	7.5	7.4	6.9
His	g/kg	4.6	4.1	3.8	3.3	3.5	3.8	3.5	3.5	3.4	3.2
Iso	g/kg	7.5	6.6	6.1	5.1	5.6	6.8	6.0	5.7	5.4	5.1
Leu	g/kg	13.4	12	11.2	10.9	11.4	13.7	12.6	12.2	11.8	11.3
Lys	g/kg	10.7	9.2	8.2	6	7.2	8.3	7.4	7.1	6.8	6.4
Met	g/kg	4.8	4.2	3.9	2.8	3.5	5.4	6.0	3.5	3.4	3.2
Phe	g/kg	8.4	7.4	7.0	6.2	6.5	6.9	6.2	6.1	5.9	5.6
Thr	g/kg	6.9	6	5.5	4.4	5.0	6.0	5.3	5.1	4.8	4.5
Val	g/kg	8.2	7.4	7.0	6.2	6.6	9.2	7.8	7.3	6.8	6.5
Ala	g/kg	9	8.1	7.6	7.1	7.8	11.6	10.1	9.4	8.7	8.3
Asp	g/kg	11.5	10.2	9.5	7.9	8.5	11.6	9.7	9.2	8.5	8.1
Cys	g/kg	2.1	1.9	1.8	1.7	1.8	1.5	1.6	1.6	1.6	1.6
Glu	g/kg	16.7	15.3	14.8	13.1	13.4	15.1	12.9	12.3	11.6	11
Gly	g/kg	9	8.2	7.6	6.6	7.5	10.7	8.9	8.2	7.6	7.1
Pro	g/kg	9.3	8.1	7.5	7.3	7.8	11.3	9.8	9.3	8.8	8.5
Ser	g/kg	9.3	8.2	7.5	6.5	7.1	7.6	7.0	6.8	6.6	6.2
Tyr	g/kg	6.2	5.4	4.9	4.1	4.6	8.3	6.8	6.2	5.6	5.4

5.4 Sensitivity Analysis Results

Based on the results of broilers and layers diet formulations, this research found that the broiler diet at grower stage has the highest combination of maize and SBM at 84.98%, which consists of maize (54.08%) and SBM (30%). On the other hand, the highest combination of maize and SBM in layer diet was lower energy limit diet in the layer 4 stage at 78.85%, which contains 61.78% maize and 17.07% SBM. Consequently, three conditions of zero inclusion level of for maize only, SBM only, and both maize and SBM only are applied to the two diets, broiler at the grower stage and layer at lower limit energy in the layer 4 stage.

Accordingly, a broiler diet and a layer diet have been formulated for the sensitivity analysis of the supply chain. Linear Programming found no solutions for the broiler diet (grower stage) under the three restrictions. The result of sensitivity broiler diet formulations depicted in Appendix 26 to 28.

Alternatively, LP successfully formulated a layer diet (layer 4 stage at the low energy limit) as summarised in Table 13. The feed cost varied from NZD 1.95 per kg to more than triple at NZD 3.12 per kg in different conditions. When zero maize inclusion, CRM dominated as main ingredient at 40%, followed by 15.29% BSFL, 9.97% wheat, and 9.86% RB, while SBM dropped to 8.6% usage compared to initial diet at 17.07%. Synthetic amino acids ranged from 0.3% per kg to 0.47% per kg. Meanwhile, when zero SBM inclusion, maize remained as the primarily ingredient at 56.16%. Other ingredients used were 2.54% FM, 11.27 CM, and 14.49% BSFL. Synthetic amino acids were incorporated from 0.08% per kg to 0.1% per kg. Lastly, when both maize and SBM were unavailable, the diet swift using 40% CRM, 23.93% BSFL, 7.68% RB, and 6.65% wheat, which these ingredients were not included in the initial diet. Copra meal on the other hand was utilised at 6.34% in both zero maize and SBM diet. The synthetic amino acids included as low as 0.003% to 0.47%. In all diets, palm oil, mineral and vitamin premixes remain stable at 5%, 1%, and 1%, respectively. Conversely, compared to zero inclusion in initial diet, sodium carbonate was used in the three scenarios ranged from 0.16% per kg to 0.25% per kg. Subsequently, zero SBM diet has the least-cost at NZD 1.95 per kg; however, all the three scenarios have a higher cost than the initial diet.

Table 13
Sensitivity Layer Diet Formulations

Ingredients (%)	Layer 4			
	Initial Diet	Zero Maize	Zero SBM	Zero Maize and SBM
Maize	61.78	-	56.16	-
Wheat	-	9.97	-	6.65
RB	-	9.86	-	7.68
CRM	-	40	-	40
SBM	17.07	8.6	-	-
MBM	-	-	-	-
FM	3.4	-	2.54	-
CM	0.93	-	11.27	6.34
BSFL	-	15.29	14.49	23.93
CLM	-	-	-	-
PO	5	5	5	5
LiSt	9.49	8.26	8.2	7.42
CaHPO ₄	-	-	-	-
Ca ₃ (PO ₄) ₂	-	-	-	-
L-Lys	-	-	0.1	0.003
DL-Met	0.11	0.3	0.08	0.3
L-Thre	-	0.47	-	0.47
NaCl	0.22	-	-	-
Na ₂ CO ₃	-	0.25	0.16	0.21
MP	1	1	1	1
VP	1	1	1	1
Cost (NZD/kg)	1.02	3.12	1.95	3.33

The nutritive values of the layer diet for the three conditions are demonstrated in Table 14. Dry matters in three scenarios diets are more than the initial diet (899 g/kg) ranging from 903 g/kg to 906 g/kg. Crude protein and fat contents in the three scenarios diets were more than initial diet at 158 g/kg to 170 g/kg and 80 g/kg to 91 g/kg, respectively. While initial diet contains 90 g/kg NDF and 33 g/kg ADF, these nutrient profiles were higher in the three scenarios than the initial diet at 92 g/kg to 125 g/kg for NDF, and 51 g/kg to exceptionally more than double at 67 g/kg for ADF. Phenomenally, calcium, sodium, AMEn, and lysine are all the same in the initial diet and the three scenarios at 38.3 g/kg, 1.4 g/kg, 12.6 MJ/kg, and 6.8 g/kg. In addition, available phosphorus across three diets were the same value of 3.5 g/kg, a slight difference to initial diet at 3.4 g/kg. In the meantime, the amino acids were differed across all diets; however, the values of methionine and threonine in zero maize and the scenario of both zero maize and SBM were higher than the initial diet. More information on each scenario at the layer 4 stage in lower limit energy diets is available from Appendix 29 to 31.

Table 14
Nutritive Values of Sensitivity Layer Diet Formulations

Nutrient Profile	Unit	Layer 4			
		Initial Diet	Zero Maize	Zero SBM	Zero Maize and SBM
DM	g/kg	899	903	903	906
Ash	g/kg	26	45	37	51
GE	MJ/kg	16	16	16	16
CP	g/kg	149	158	159	170
Fat	g/kg	80	86	90	91
Starch	g/kg	401	383	364	357
NDF	g/kg	90	92	148	125
ADF	g/kg	33	51	61	67
Ca	g/kg	38.3	38.3	38.3	38.3
Mg	g/kg	3.1	3.6	3.1	3.5
K	g/kg	6	8.2	6.2	8.4
Na	g/kg	1.4	1.4	1.4	1.4
AvP	g/kg	3.4	3.5	3.5	3.5
AMEn	MJ/kg	12.6	12.6	12.6	12.6
Arg	g/kg	8.5	7.5	8	7.7
His	g/kg	3.6	3	3.1	2.9
Iso	g/kg	5.4	5.5	5.4	5.8
Leu	g/kg	11.8	9.1	11.4	9.4
Lys	g/kg	6.8	6.8	6.8	6.8
Met	g/kg	3.4	5.2	3.4	5.4
Phe	g/kg	6.4	5.5	5.8	5.5
Thr	g/kg	4.7	9.3	4.7	9.5
Val	g/kg	6.2	7	7.4	8
Ala	g/kg	7.7	7.1	8.8	8.2
Asp	g/kg	8.1	9.4	9.2	10.5
Cys	g/kg	2	1.2	1.4	1
Glu	g/kg	11.8	13	13.1	14.2
Gly	g/kg	6.9	6.3	7.5	7
Pro	g/kg	8.4	7.7	8.5	8
Ser	g/kg	7	5.9	6.1	5.7
Tyr	g/kg	4.6	6.2	6.1	7.4

Chapter 6: General Discussion

The mixture of local and imported feed ingredients in diet formulation involves a range of interconnected factors. This thesis presents a total of 28 least-cost diet formulations, consisting of 25 initial diets and 3 additional diets under sensitivity analysis based on the dietary requirements of broilers and layers. Linear programming models were used to formulate diets by combining 18 feed ingredients sourced locally in WP, traded across islands in Indonesia, or imported. Tables 7 to 14 demonstrate that these feed formulations meet nutrient requirements while minimising feed costs given supply chain disruptions. The LP models are developed by considering all possible ingredient combinations, the nutrient profile, dietary needs, and constraints, and then solved using Excel. Additionally, integrating supply chain considerations allows for balancing diet formulations with economic factors and ingredient availability, tailored to poultry nutritional needs. Table 15 illustrates ingredient availability and their usage in the least-cost diet formulations.

Table 15
Ingredients Availability and the Usage of the Ingredients in the Least-Cost Diet Formulations

Ingredients	Production			Availability in Natural Form			Inclusion Rate based on LP Modelling (%)
	West Papua Province	Other regions in Indonesia	Import	West Papua Province	Other regions in Indonesia	Import	
Maize	✓	✓	✓	✓	✓	✓	5.56-66
Wheat	-	✓	✓	-	✓	✓	6.65-9.97 ^a
RB	✓	✓	✓	✓	✓	✓	7.68-9.86 ^a
CRM	-	✓	✓	✓	✓	✓	3.25-40
SBM	-	✓	✓	✓	✓	✓	0.68-30
MBM	-	✓	✓	✓	✓	✓	0.37-2.27
FM	-	✓	✓	✓	✓	✓	0.34-7.29
CM	✓	✓	✓	✓	✓	✓	0.02-19.63
BSFL	-	✓	✓	✓	✓	✓	1.73-23.93
CLM	-	✓	✓	✓	✓	✓	0
PO	✓	✓	✓	✓	✓	✓	2.28-6
LiSt	-	✓	✓	✓	✓	✓	0.94-9.76
CaHPO ₄	-	✓	✓	-	✓	✓	0
Ca ₃ (PO ₄) ₂	-	✓	✓	-	✓	✓	0
L-Lys	-	✓	✓	-	✓	✓	0.0006-0.18
DL-Met	-	✓	✓	-	✓	✓	0.007-0.8
L-Thre	-	✓	✓	-	✓	✓	0.003-0.47
NaCl	-	✓	✓	✓	✓	✓	0.16-0.4
Na ₂ CO ₃	-	✓	✓	-	✓	✓	0.01-0.29
MP	-	✓	✓	-	✓	✓	1
VP	-	✓	✓	-	✓	✓	1

Note:

Available (✓)

Not Available (-)

^a Only available under sensitivity analysis

6.1 Nutrient Composition and Supply Chain Considerations

The LP modelling has effectively developed diets that meet the minimum requirements of broilers and layers in this research, combining multiple supply streams of feed ingredients. One of the biggest challenges in poultry production is providing nutrition that fully meets the physiological requirements and performance potential of each poultry category while maintaining financial profitability (Son et al., 2024). The feed rations and costs vary depending on the ingredients, reflecting the different prices and nutrient profiles of the chosen ingredients in the diets. This research demonstrates that LP modelling has successfully created diets combining multiple supply sources of ingredients that meet the nutrient needs of poultry at different growth stages, including critical nutrients such as CP, fat, calcium, phosphorus, AMEn, lysine, methionine, and other nutrient profiles, all at the least cost. These findings support existing literature on the utilisation of LP for optimising poultry diet formulations (Irawan et al., 2022; Owolabi et al., 2015; Scanes & Christensen, 2020).

Furthermore, maize and SBM play a critical role in formulated diets in this research. Maize is the primary ingredient, comprising a minimum of 5.56-66% of all formulated diets, likely due to its cost-effectiveness and nutrient profile, providing sources of energy and protein. In this research, CRM has surprisingly contributed from 3.25% to 40% inclusion rate, with the majority of the inclusion of CRM found to be in the early stages of layer diets. At the same time, this occurred when the inclusion of maize was at its lowest level, at 5.56% to 6.78% at the lower limit of energy in layer diets Table 9. This suggests that CRM contributed partially to the energy density needed for poultry, aligning with the literature stating that CRM can be incorporated into diets (Glatz, 2017; Khempaka et al., 2022). Similarly, SBM as a protein source ranges from as little as 0.68-30% in the diets examined. This finding of low inclusion of SBM could suggest that there are other ingredients incorporated into diets that can substitute for SBM in the diets partially, which provide nutrients needed for poultry.

However, some formulations included ingredients like CM and BSFL, such as in broilers (1.52-6.23% CM and 1.73-3.72% BSFL) in Table 7 and layers (0.02%-20% CM and 3.11-21.48% BSFL) in Tables 9 and 11. The inclusion of CM supports findings from Sugiharto et al. (2018) and Adjis et al. (2021), improving poultry performance. These differences likely show changes in protein sources and the low inclusion of SBM. Energy needs for layers in Table 11 showed SBM

inclusion from 12.35-30% during early stages until pre-lay, then decreasing drastically to 0.68-7.05%. Conversely, BSFL contributed 21.48% during the peaking stage before gradually declining at the end of the layer phase (Table 11). The inclusion of BSFL supports findings from other studies indicating its potential as a replacement for other protein sources (Makkar et al., 2014).

Ingredients that are available in all supply sources in WP, other regions in Indonesia, and imports, include maize, RB, CM, and PO. Even though maximum inclusion of maize can reach 66% in this research and considering the supply chain of maize, WP still needs to import maize from other regions. Some findings, such as RB, supplied 7.68-9.86% in Table 13, contributing to energy and fibre intake in the diet. This finding aligns with the literature on the use of RB as an alternative energy source in various studies. (Cheeke, 2005; Leeson & Summers, 2001, 2005; Sugiharto et al., 2018). Similarly, the inclusion of PO into diets is within 1.67-6%. The usage of PO is to meet the energy and fat content (Long et al., 2019; Saminathan et al., 2022). Among other ingredients, PO is the most reliable since it is available in all sources, from locally produced, inter-island trading and imports.

Some ingredients incorporated into diets include limestone (0.94-9.76%) and mineral-vitamin premixes (1% each premix). Limestone provides the main source of calcium, critical for poultry. Similarly, even though vitamin and mineral premixes each account for only 1%, including these ingredients is not problematic, although the cost of these ingredients is quite high. Despite the unreliability of synthetic amino acids and premixes in WP, they are essential ingredients that are needed in small amounts. Also, synthetic amino acids are recommended for low inclusion levels, importing these ingredients remains a practical option for their usage.

Meanwhile, animal protein sources are used at low to moderate levels, including MBM (0.37-2.27%) and FM (0.34-7.29%). Although these ingredients are not locally produced in WP, they are included in the diets due to their nutrient content and cost transparency. However, they are also available in natural forms in WP, these ingredients could be considered as potential future feed options when formulated in WP.

Conversely, some ingredients, including CLM, DCP, and TCP, were not included in any diet formulations in this research for several reasons. Although they are available through some supply chain sources within the country and via imports, these ingredients face competition

from others in terms of price and nutritional profile. Furthermore, CLM has a lower nutritional profile and is relatively expensive, despite being widely available in natural forms in WP. On the other hand, DCP and TCP were only available from other regions and global markets and were costly compared to limestone, which was abundant in WP, serving as the primary calcium source. Therefore, CLM, DCP, and TCP were not included in the diets due to the cost and nutritional values.

6.2 Feed Formulation and Supply Chain Implications

In investigating the supply chain of the feed ingredients in formulating poultry diets, a broiler diet and a layer diet have been formulated for the sensitivity analysis from the initial 25 formulated diets. Three scenarios or restrictions were applied to one broiler diet (Grower) and one layer diet (Layer 4 at minimum energy limit) out of the highest concentration of maize and SBM.

Linear Programming found no solutions for the broiler diet (grower stage) under the three restrictions. This finding suggests that the scenarios of no maize, no SBM, and both combined result in infeasible solutions for LP to find the least-cost while meeting the nutritional requirements. The constraints were so tight that posing LP found no solution. This shows directly that the grower's diet had significant reliance on maize and SBM, given the nutritional requirements and costs; other optional ingredients will not satisfy either the cost relevance or the nutritional contents, hence, posing an LP to find no solution.

In contrast, LP has found solutions for the chosen layer diet (layer 4 at the low energy limit). There is a clear link between ingredient use and their supply chains for feed ingredients. Table 13 shows that when maize was unavailable, the LP had to find other alternative ingredients to meet the requirements. Likewise, CRM accounts for up to 40% inclusion as a source of energy and utilising wheat and RB, just under 10% for each ingredient. This solution aligns with wheat is considered the equivalent of maize in the animal feed industry (Cheeke, 2005). Wheat has a higher protein content and a similar energy content to maize, which can substitute maize with no adverse impacts on poultry (Cheeke, 2005).

However, the surprising finding was that wheat and RB were only incorporated into the diets when maize was unavailable. Although the price of wheat is expensive, the nutrient composition of wheat meets the requirements of diets, and it is within the feasible solution of LP. In pushing the cost within a feasible solution, LP found RB as another energy source to be incorporated along with wheat. Since both wheat and RB have higher values of NDF and ADF than maize (see Table 1); subsequently, it further proved that the diets with the inclusion of wheat and RB had higher levels of NDF and ADF compared to diets where maize was included (Table 14). Even though all of the diets have met the layer's requirement, this finding suggests that the diet in this research relied heavily on maize as the main ingredient. The substitution of maize with RB, which is widely available across multiple supply sources, does not guarantee a decline in production cost; instead, the inclusion of RB along with wheat has led to a higher cost. The total cost of when zero maize (NZD 3.13 per kg) and both zero maize and SBM (3.33) were more than triple the initial diet cost (NZD 1.02 per kg).

Although the absence of SBM does not present a dramatic shift in cost as the absence of maize or both ingredients, the cost of zero SBM (NZD 1.95 per kg) was almost double that of the initial diet. This also suggested that this diet relies on SBM to meet protein content, even though in these sensitivity scenarios, FM, CM, and BSFL contributed to protein content along with the high inclusion of maize at 56.16%.

Since LP find no solutions to the selected broiler diet (grower), and all of the sensitivity scenarios in layers have a higher cost than the initial diet, it is appropriate to state that ingredient choices and their supply chain influence cost variations. The supply chain disruptions of maize and SBM unavailability influence the costs and the nutrient composition of diets. The three factors influencing ingredient inclusion levels are availability, nutritional values, and cost of feed ingredients. The absence of one of the key ingredients can lead to higher production costs.

While the availability of maize and SBM influence the LP results, it is worth noting that the potential usage of feedstuff in WP substituting for maize or SBM. Although the costs and nutritional values influence the inclusion of feed ingredients, the availability of a variety of feedstuffs in WP indicates a broader potential for diet formulation. The notable finding is that 12 ingredients are all naturally available in WP, including maize and SBM. However, LP found no solution that includes all these ingredients in a single diet, likely due to the costs of the

feedstuffs and their nutrient profiles. If these ingredients can be produced at scale and low prices in WP, it could improve logistical feasibility by reducing dependence on supplies from other regions in Indonesia or imports. Therefore, increasing local production of these ingredients, along with CLM and sodium chloride as alternative options, can improve flexibility and sustainability in poultry diet formulation, ultimately lowering overall costs in WP.

Addressing ingredient availability from local production, other regions in Indonesia, and imports in this study offers insights into optimising diet formulations in WP. While WP produces ingredients such as maize, RB, CM, and PO, the volume and quality of these ingredients restrict their reliability for larger-scale feed industry production in WP. However, these findings indicate that WP has significant potential because many ingredients used in this study can be utilised in poultry diets. Improving local production of these feed ingredients could enhance feed output and decrease dependence on imports. The results imply that combining LP modelling, ingredient nutrient profiles, and supply chain considerations can help guide the formulation of poultry diets in similar regional settings.

Chapter 7: Recommendations and Conclusion

This chapter presents recommendations, conclusion, limitations, and future research implications. The recommendations cover offering ingredient flexibility, substitution, and diversification; strengthening supply chain partnerships; developing strategies for storage and infrastructure; proposing government support and policies; and conducting research on ingredient digestibility and nutritional values. The conclusion will summarise the findings and discussions of this thesis. Finally, limitations and future research implications will be addressed in this chapter.

7.1 Recommendations

7.1.1 Offering Ingredient Flexibility, Substitution, and Diversification

Allowing flexibility, substitution and diversification of ingredients can optimise diet formulations. This flexibility is useful when some ingredients are unavailable at certain times of the year; the feed mill can substitute with other ingredients that have similar nutrient profiles (Abdollahi & Ravindran, 2017). Even with effective storage and inventory management, the formulation should be tailored to each region, considering the availability and cost of both imported and local feed ingredients, as well as their environmental impact (Heidari et al., 2021). Iyai et al. (2023) proposed strategies to boost livestock development in WP, including encouraging and increasing local feed ingredient production, sourcing and development, empowering local communities, and strengthening agricultural support. Therefore, diversifying ingredients, especially those sourced locally, can reduce reliance on specific ingredients can be reduced (Abdollahi & Ravindran, 2017).

7.1.2 Strengthening Supply Chain Partnerships

Supplier diversification is essential for each critical ingredient and logistics, both in Indonesia and internationally. It offers sourcing flexibility and reduces the impact of supply chain disruptions (Adobor & McMullen, 2007). Price volatility in global markets can significantly impact the poultry industry (Khan & Yu, 2019), including WP. Currency fluctuations and shifts in global demand directly influence ingredient prices, affecting feed production (Arizona et al., 2023). Additionally, a company should view its diverse suppliers as strategic partners (Adobor & McMullen, 2007). Long-term contracts or partnerships are vital to ensure a stable supply of key ingredients and to negotiate transportation and logistics at reasonable costs (Khan & Yu,

2019). Building strong relationships with suppliers is strategic, as these partnerships can add value and create a competitive advantage (Adobor & McMullen, 2007). Effective relationships should clearly define expectations for suppliers, partnership goals, and company programmes (Adobor & McMullen, 2007). Since this research relies on secondary data from online reports, marketplaces, news, and average costs, sourcing ingredients locally in WP can help minimise prices. There should be opportunities to establish partnerships that secure ingredient availability or achieve lower prices than the general market. Developing strategic plans to reach these goals and regularly assessing relationships and performance are crucial for managing the supply chain and strategic alliances (Adobor & McMullen, 2007). Therefore, supplier diversification through strategic partnerships can help mitigate the adverse effects of sudden price changes and supply chain fluctuations.

7.1.3 Developing Strategies for Storage and Infrastructure Development

West Papua lacks adequate storage facilities, so WP should invest in developing the region's storage infrastructure. Stakeholders and the government can work together to establish modern storage options (Khan & Yu, 2019). Improved storage facilities would enable year-round ingredient availability and reduce spoilage (Khan & Yu, 2019). Investment in storage can enhance the flow of goods within the logistics network and strengthen regional and business competitiveness.

Similar to storage investment, infrastructure development can strengthen the supply chain of feed ingredients. It can create more business opportunities for growth by providing easy access to the logistics and transportation industries (Khan & Yu, 2019; Simatupang, 2013). The Indonesian government should invest in infrastructure, such as developing an improved road network that connects domestic ports to nearby agricultural regions and inland infrastructure in each area (Ferlito & Respatiadi, 2018), including enhancements in WP infrastructure (Iyai et al., 2023). Zaman et al. (2015) noted that port development can lower transportation and production costs. They also mentioned that reducing production costs can lead to lower selling prices, giving a competitive edge (Zaman et al., 2015). In turn, infrastructure supports the entire business chain, activities, and efficient production processes (Ferlito & Respatiadi, 2018). Therefore, investing in infrastructure can enhance the feed ingredient supply chain when formulating diets.

7.1.4 Proposing Government Support and Policy

The government can create policies that support local feed farmers and businesses. An example of the Indonesian government protecting local farmers and businesses is the Indonesian Minister of Trade Regulation (Permendag) No. 21 of 2018, which specifically limits importing maize for feed formulation from other countries (Ariyanto et al., 2023). This regulation was introduced to safeguard domestic maize producers from international competition and to boost the country's competitiveness in maize production (Ariyanto et al., 2023). Indonesia aims to increase national maize production and improve farmers' access to maize markets (Ariyanto et al., 2023). In line with restricting maize imports for feeds, major feed mill companies can focus on utilising local production in diet formulation (Ariyanto et al., 2023). Likewise, when local maize production is low, the Indonesian National Food Logistics (Badan Urusan Logistik (BULOG)) can import maize for feeds based on assignments and government approval (Ariyanto et al., 2023). The Indonesian government can implement similar regulations for other local feed ingredients that are plentiful, nutrient-rich, and effective for diet formulation. In addition, policies can play a crucial role in supporting and addressing the key issues faced by local businesses to improve the supply chain (Aminuddin & Okdinawati, 2023). Supply chain policies promote sustainable development, animal welfare, and food safety within the industry (Aminuddin & Okdinawati, 2023). Therefore, the government can develop policies to strengthen and safeguard the country and local businesses, ultimately enhancing the supply chain.

7.1.5 Undertaking Research on Ingredients Digestibility and Nutritive Values

Since WP has very limited information on the ingredients used in these diets, research and development on locally produced ingredients and their digestibility and nutritional values are necessary to provide up-to-date and accurate data that can influence the formulations. Not only the ingredients included in the diets, but also other potential ingredients that are widely found in WP, should be studied. Thereupon, with nearly accurate values of digestibility and nutritional content, this can optimise diet formulation using fully or partially locally produced ingredients. The values of data collected in this research are standard. Likewise, the data might be different if the research had conducted its own experiment and its own values. However, in doing so, it needs much investigation into all of the potential ingredients, which may lead to massive investment in studying all the nutritive values of ingredients for poultry.

7.2 Conclusion

This research has examined the key factors impacting the livestock feed components supply chain in formulating poultry diets in MKW, WP, Indonesia. These key factors include price and availability of feed ingredients, transportation and logistics, and dependence on imported ingredients. In creating feed formulation, the main goal was to meet the nutritional poultry requirements by utilising available ingredients at the lowest cost possible. This research utilised linear programming as the main tool to formulate poultry diets and to run the sensitivity analysis of the feed ingredients.

West Papua's supply chain faces many challenges due to its dependence on domestic and imported ingredients, leading to price vulnerability in WP. Some aspects that can disrupt the supply chain include limited locally grown ingredients, delayed transportation, and high transportation and logistics costs. This study found that when supply chain disruptions occurred under the condition of zero maize and SBM inclusions, WP can partially substitute imported ingredients. However, the result also established that the cost of the feed formulation increases under the given situation, underlining that the initial chosen diets relied on maize and SBM. Since WP has a limited production of maize and no production of SBM in WP, it is clear that the supply chain disruptions of these ingredients can influence the feed production cost and the feed composition. As a result, this research recommends that improving local feed ingredient production, allowing ingredient flexibility in formulation, and strengthening supply chain partnerships can help mitigate the adverse effects of price changes and supply chain fluctuations. Furthermore, developing strategies for storage and infrastructure development, and proposing government support and policy can ultimately enhance the feed ingredient supply chain. Finally, integrating supply chain analysis and linear programming in optimising poultry feed formulation can promote sufficiency, cost-effectiveness and sustainability in WP.

7.3 Limitations

There are some limitations in this research. This research was limited to only one province, West Papua Province in Indonesia. The results of this research are only applicable to regions that face similar situations. Furthermore, this thesis relies profoundly on secondary data sources for the market data and nutritional values of ingredients. Accordingly, the ingredient prices depend on the online market data from different sources, subject to price fluctuations and exchange rates. A precision to the updated price is needed for more accurately results. Similarly, the nutritive values were derived from different sources, whose approach to finding the nutritive values of certain ingredients might vary from each other. This might lead to different results if this research only utilises a single data-based source.

7.4 Future Research Implications

Although all the diets formulated by LP modelling in this research meet the nutritional specifications for broilers and layers, future trials are necessary to assess their direct impacts on poultry. Additionally, updating the nutritional values of available feed ingredients in WP and current market data is important for more accurate results. Furthermore, future research should include more local ingredients in diet formulations to provide greater flexibility in identifying the least-cost diet.

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Appendices

Appendix 1: Result of broiler starter 1 (Days 0-12)

Variable	Amount	Valid Cost Range			Constraint	Amount	Valid RHS Range		
		Lower Bound	Current	Upper Range			Lower Bound	Current	Upper Range
Maize	0.5117	0.83	0.86	3.93	Weight	1	0.98	1	1.03
Wheat	0	1.44	11.73	1E+300	DM	891.33	-1E+300	0	891.33
RB	0	-6.62	0.79	1E+300	Ash	43.37	-1E+300	0	43.37
CRM	0	-1.92	0.63	1E+300	GE	16.85	-1E+300	0	16.85
SBM	0.3	-2E+13	1.59	9.53	CP	243.14	-1E+300	230	243.14
MBM	0	-11.29	1.78	1E+300	Fat	59.83	-1E+300	0	59.83
FM	0.0639	-85.90	1.78	2.32	Starch	333.45	-1E+300	0	333.45
CM	0.0152	-16.83	0.52	0.80	NDF	105.5	-1E+300	0	105.50
BSFL	0.0371	7.53	8.29	129.28	ADF	44.52	-1E+300	0	44.52
CLM	0	-1.99	7.35	1E+300	Ca	13	-1E+300	9.5	13
PO	0.0239	-60.85	1.67	1.77	Ca	13	9.5	13	17.02
LiSt	0.0196	-4.45	0.06	0.52	Mg	2.06	-1E+300	0.5	2.06
CaHPO ₄	0	-59.29	2.52	1E+300	Mg	2.06	2.06	3	1E+300
Ca ₃ (PO ₄) ₂	0	-72.33	7.35	1E+300	K	9	-1E+300	6	9
L-Lys	0.0017	-606.09	6.09	50.71	K	9	8.77	9	9.10
DL-Met	0.0019	1.30	11.79	56.50	Na	2.3	-1E+300	1.8	2.30
L-Thre	0.0012	1.16	8.39	31.16	Na	2.3	1.8	2.3	2.41
NaCl	0.0037	-122.74	0.8	0.87	AvP	5	-1E+300	4.5	5.00
Na ₂ CO ₃	0	0.80	0.94	1E+300	AvP	5	4.73	5	5.12
MP	0.01	-1E+300	3.59	1E+300	AMEn	12.40	11.88	12.4	13.19
VP	0.01	-1E+300	1.67	1E+300	Arg	14	13.94	14	14.58
					His	5.45	-1E+300	0	5.45
					Iso	8.88	-1E+300	8.8	8.88
					Leu	17.18	-1E+300	14.5	17.18
					Lys	13.20	11.81	13.2	20.58
					Met	5.50	3.63	5.5	8.58
					Phe	10	-1E+300	0	10.00
					Thr	8.80	7.61	8.8	15.51
					Val	10.1	-1E+300	10	10.10
					Ala	11.53	-1E+300	0	11.53
					Asp	13.77	-1E+300	0	13.77
					Cys	2.66	-1E+300	0	2.66
					Glu	19.71	-1E+300	0	19.71
					Gly	10.82	-1E+300	0	10.82
					Pro	12.19	-1E+300	0	12.19
					Ser	11.01	-1E+300	0	11.01
					Tyr	7.84	-1E+300	0	7.84
					Maize	51.17	51.17	60	1E+300
					Wheat	0	0	15	1E+300
					RB	0	0	10	1E+300
					CRM	0	0	40	1E+300
					SBM	30.00	16.54	30	30.74
					MBM	0	0	6	1E+300
					FM	6.39	6.39	8	1E+300
					CM	1.52	1.52	20	1E+300
					BSFL	3.71	3.71	20	1E+300
					CLM	0	0	20	1E+300
					PO	2.39	2.39	6	1E+300

					LiSt	1.96	1.96	3	1E+300	
					CaHPO ₄	0	0	1.5	1E+300	
					Ca ₃ (PO ₄) ₂	0	0	1.5	1E+300	
					L-Lys	0.17	0.17	1.1	1E+300	
					DL-Met	0.19	0.19	0.5	1E+300	
					L-Thre	0.12	0.12	0.8	1E+300	
					NaCl	0.37	0.37	0.4	1E+300	
					Na ₂ CO ₃	0	0	0.4	1E+300	
					MP	1	0	1	3.37	
					VP	1	0	1	3.37	
Objective Cost: 1.49/kg										

Appendix 2: Result of broiler grower (Days 11-24)

Variable	Amount	Valid Cost Range			Constraint	Amount	Valid RHS Range		
		Lower Bound	Current	Upper Range			Lower Bound	Current	Upper Range
Maize	0.5408	0.42	0.86	0.90	Weight	1	0.97	1	1.03
Wheat	0	1.07	11.73	1E+300	DM	890.52	-1E+300	0	890.52
RB	0	-2.02	0.79	1E+300	Ash	36.77	-1E+300	0	36.77
CRM	0	-0.01	0.63	1E+300	GE	17.21	-1E+300	0	17.21
SBM	0.3	-7E+13	1.59	4.86	CP	220.40	-1E+300	215	220.40
MBM	0	-6.73	1.78	1E+300	Fat	71.08	-1E+300	0	71.08
FM	0.0345	0.83	1.78	5.99	Starch	352.16	-1E+300	0	352.16
CM	0.0295	0.03	0.52	1.07	NDF	111.41	-1E+300	0	111.41
BSFL	0.0173	7.51	8.29	312.25	ADF	46.27	-1E+300	0	46.27
CLM	0	0.79	7.35	1E+300	Ca	7.5	3.23	7.5	13
PO	0.0392	1.53	1.67	3.15	Ca	7.5	7.5	13	1E+300
LiSt	0.011	-0.62	0.06	0.90	Mg	1.82	-1E+300	0.5	1.82
CaHPO ₄	0	-26.16	2.52	1E+300	Mg	1.82	1.82	3	1E+300
Ca ₃ (PO ₄) ₂	0	-31.82	7.35	1E+300	K	9	-1E+300	6	9
L-Lys	0.0018	-226.62	6.09	34.90	K	9	8.44	9	9.94
DL-Met	0.002	0.61	11.79	429.70	Na	1.8	0.54	1.8	2.27
L-Thre	0.0011	0.19	8.39	264.73	Na	1.8	1.8	2.3	1E+300
NaCl	0	0.79	0.8	1E+300	AvP	4.2	-1E+300	4.1	4.2
Na ₂ CO ₃	0.0029	-0.58	0.94	0.95	AvP	4.2	4.1	4.2	4.68
MP	0.01	-1E+300	3.59	1E+300	AMEn	12.8	11.93	12.8	13.26
VP	0.01	-1E+300	1.67	1E+300	Arg	13.03	-1E+300	12.7	13.03
					His	5.03	-1E+300	0	5.03
					Iso	8.05	-1E+300	8	8.05
					Leu	15.94	-1E+300	13	15.94
					Lys	11.8	10.37	11.8	19.16
					Met	5.1	3.16	5.1	8.11
					Phe	9.3	-1E+300	0	9.30
					Thr	7.9	6.83	7.9	14.75
					Val	9.1	9.03	9.1	10.75
					Ala	10.17	-1E+300	0	10.17
					Asp	12.51	-1E+300	0	12.51
					Cys	2.59	-1E+300	0	2.59
					Glu	18.17	-1E+300	0	18.17
					Gly	9.24	-1E+300	0	9.24
					Pro	11.20	-1E+300	0	11.20
					Ser	10.10	-1E+300	0	10.10
					Tyr	6.92	-1E+300	0	6.92
					Maize	54.08	54.08	60	1E+300

					Wheat	0	0	20	1E+300
					RB	0	0	10	1E+300
					CRM	0	0	40	1E+300
					SBM	30	29.02	30	33.14
					MBM	0	0	6	1E+300
					FM	3.45	3.45	8	1E+300
					CM	2.95	2.95	20	1E+300
					BSFL	1.73	1.73	20	1E+300
					CLM	0	0	20	1E+300
					PO	3.92	3.92	6	1E+300
					LiSt	1.1	1.1	3	1E+300
					CaHPO ₄	0	0	1.5	1E+300
					Ca ₃ (PO ₄) ₂	0	0	1.5	1E+300
					L-Lys	0.18	0.18	1.1	1E+300
					DL-Met	0.20	0.2	0.5	1E+300
					L-Thre	0.11	0.11	0.8	1E+300
					NaCl	0	0	0.4	1E+300
					Na ₂ CO ₃	0.29	0.29	0.4	1E+300
					MP	1	0	1	4.15
					VP	1	0	1	4.15

Objective Cost: 1.33/kg

Appendix 3: Result of broiler finisher 1 (25-39)

Variable	Amount	Valid Cost Range			Constraint	Amount	Valid RHS Range		
		Lower Bound	Current	Upper Range			Lower Bound	Current	Upper Range
Maize	0.5284	0.82	0.86	1.16	Weight	1	0.99	1	1
Wheat	0	0.94	11.73	1E+300	DM	892.77	-1E+300	0	892.77
RB	0	0.12	0.79	1E+300	Ash	33.16	-1E+300	0	33.16
CRM	0	0.60	0.63	1E+300	GE	17.37	-1E+300	0	17.37
SBM	0.3	-1E+14	1.59	2.44	CP	205.57	-1E+300	195	205.57
MBM	0	-1.01	1.78	1E+300	Fat	86.54	-1E+300	0	86.54
FM	0.0226	0.88	1.78	2.4	Starch	344.02	-1E+300	0	344.02
CM	0.0415	-3.95	0.52	0.6	NDF	112.33	-1E+300	0	112.33
BSFL	0	2.88	8.29	1E+300	ADF	46.56	-1E+300	0	46.56
CLM	0	0.76	7.35	1E+300	Ca	10.19	-1E+300	6.5	10.19
PO	0.0582	0.75	1.67	1.72	Ca	10.19	10.19	11.8	1E+300
LiSt	0.0213	-0.45	0.06	0.1	Mg	1.97	-1E+300	0.5	1.97
CaHPO ₄	0	-6.00	2.52	1E+300	Mg	1.97	1.97	3	1E+300
Ca ₃ (PO ₄) ₂	0	-7.31	7.35	1E+300	K	9	-1E+300	6	9
L-Lys	0.0016	-19.90	6.09	26.65	K	9	8.92	9	9.1
DL-Met	0.002	0.91	11.79	109.61	Na	1.8	0.41	1.8	1.96
L-Thre	0.0009	0.61	8.39	67.09	Na	1.8	1.8	2.3	1E+300
NaCl	0.0036	0.06	0.8	0.85	AvP	3.8	-1E+300	3.6	3.8
Na ₂ CO ₃	0	0.88	0.94	1E+300	AvP	3.8	3.78	3.8	3.81
MP	0.01	-1E+300	3.59	1E+300	AMEn	13	12.84	13	13.07
VP	0.01	-1E+300	1.67	1E+300	Arg	12.47	-1E+300	11.7	12.47
					His	4.74	-1E+300	0	4.74
					Iso	7.5	7.5	7.5	7.52
					Leu	14.99	-1E+300	11.9	14.99
					Lys	10.8	9.53	10.8	17.51
					Met	4.8	2.86	4.8	6.63
					Phe	8.82	-1E+300	0	8.82
					Thr	7.2	6.32	7.2	13.65

					Val	8.41	-1E+300	8.4	8.41
					Ala	9.25	-1E+300	0	9.25
					Asp	11.62	-1E+300	0	11.62
					Cys	2.51	-1E+300	0	2.51
					Glu	17.15	-1E+300	0	17.15
					Gly	8.32	-1E+300	0	8.32
					Pro	10.42	-1E+300	0	10.42
					Ser	9.5	-1E+300	0	9.5
					Tyr	6.24	-1E+300	0	6.24
					Maize	52.84	52.84	70	1E+300
					Wheat	0	0	25	1E+300
					RB	0	0	20	1E+300
					CRM	0	0	40	1E+300
					SBM	30	29.88	30	30.03
					MBM	0	0	8	1E+300
					FM	2.26	2.26	10	1E+300
					CM	4.15	4.15	20	1E+300
					BSFL	0	0	20	1E+300
					CLM	0	0	20	1E+300
					PO	5.82	5.82	6	1E+300
					LiSt	2.13	2.13	3	1E+300
					CaHPO ₄	0	0	1.5	1E+300
					Ca ₃ (PO ₄) ₂	0	0	1.5	1E+300
					L-Lys	0.16	0.16	1	1E+300
					DL-Met	0.20	0.20	0.38	1E+300
					L-Thre	0.09	0.09	0.74	1E+300
					NaCl	0.36	0.36	0.4	1E+300
					Na ₂ CO ₃	0	0	0.4	1E+300
					MP	1	0.58	1	1.97
					VP	1	0.58	1	1.97

Objective Cost: 1.19/kg

Appendix 4: Result of broiler finisher 2 (40-51)

Variable	Amount	Valid Cost Range			Constraint	Amount	Valid RHS Range		
		Lower Bound	Current	Upper Range			Lower Bound	Current	Upper Range
Maize	0.5465	0.84	0.86	0.86	Weight	1	1	1	1.01
Wheat	0	0.87	11.73	1E+300	DM	891.84	-1E+300	0	891.84
RB	0	0.53	0.79	1E+300	Ash	31.79	-1E+300	0	31.79
CRM	0	0.63	0.63	1E+300	GE	17.5	-1E+300	0	17.50
SBM	0.2761	1.57	1.59	1.81	CP	195.74	-1E+300	180	195.74
MBM	0	0.42	1.78	1E+300	Fat	87.9	-1E+300	0	87.9
FM	0.0148	1.73	1.78	2.22	Starch	355.6	-1E+300	0	355.6
CM	0.0623	-2.40	0.52	0.53	NDF	121.92	-1E+300	0	121.92
BSFL	0	2.33	8.29	1E+300	ADF	50.24	-1E+300	0	50.24
CLM	0	0.65	7.35	1E+300	Ca	6.22	-1E+300	6	6.22
PO	0.06	-2E+15	1.67	1.74	Ca	6.22	6.22	11.8	1E+300
LiSt	0.012	0.03	0.06	0.11	Mg	1.77	-1E+300	0.5	1.77
CaHPO ₄	0	-2.1	2.52	1E+300	Mg	1.77	1.77	3	1E+300
Ca ₃ (PO ₄) ₂	0	-2.5	7.35	1E+300	K	9	-1E+300	6	9
L-Lys	0.0018	-1.08	6.09	6.67	K	9	8.53	9	9.02
DL-Met	0.0018	0.95	11.79	52.08	Na	1.8	0.34	1.8	1.9
L-Thre	0.0009	0.64	8.39	11.41	Na	1.8	1.8	2.3	1E+300
NaCl	0.0038	0.07	0.8	0.85	AvP	3.6	-1E+300	3.4	3.6

Na ₂ CO ₃	0	0.88	0.94	1E+300	AvP	3.6	3.4	3.6	3.74
MP	0.01	-1E+300	3.59	1E+300	AMEn	13.1	12.89	13.1	13.11
VP	0.01	-1E+300	1.67	1E+300	Arg	11.94	-1E+300	11.2	11.94
					His	4.49	-1E+300	0	4.49
					Iso	7.06	-1E+300	7	7.06
					Leu	14.35	-1E+300	11.2	14.35
					Lys	10.2	8.74	10.2	15.55
					Met	4.5	2.81	4.5	5.87
					Phe	8.39	-1E+300	0	8.39
					Thr	6.8	5.94	6.8	10.94
					Val	8	7.97	8	8.27
					Ala	8.77	-1E+300	0	8.77
					Asp	10.99	-1E+300	0	10.99
					Cys	2.42	-1E+300	0	2.42
					Glu	16.43	-1E+300	0	16.43
					Gly	7.76	-1E+300	0	7.76
					Pro	9.93	-1E+300	0	9.93
					Ser	8.96	-1E+300	0	8.96
					Tyr	5.86	-1E+300	0	5.86
					Maize	54.65	54.65	70	1E+300
					Wheat	0	0	25	1E+300
					RB	0	0	20	1E+300
					CRM	0	0	40	1E+300
					SBM	27.61	27.61	30	1E+300
					MBM	0	0	8	1E+300
					FM	1.48	1.48	10	1E+300
					CM	6.23	6.23	20	1E+300
					BSFL	0	0	20	1E+300
					CLM	0	0	20	1E+300
					PO	6	5.96	6	6.93
					LiSt	1.2	1.2	3	1E+300
					CaHPO ₄	0	0	1.5	1E+300
					Ca ₃ (PO ₄) ₂	0	0	1.5	1E+300
					L-Lys	0.18	0.18	0.85	1E+300
					DL-Met	0.18	0.18	0.32	1E+300
					L-Thre	0.09	0.09	0.68	1E+300
					NaCl	0.38	0.38	0.4	1E+300
					Na ₂ CO ₃	0	0	0.4	1E+300
					MP	1	0	1	1.06
					VP	1	0	1	1.06

Objective Cost: 1.16/kg

Appendix 5: Result of broiler finisher 3 (52-market)

Variable	Amount	Valid Cost Range			Constraint	Amount	Valid RHS Range		
		Lower Bound	Current	Upper Range			Lower Bound	Current	Upper Range
Maize	0.5088	0.83	0.86	0.86	Weight	1	0.99	1	1.01
Wheat	0	0.87	11.73	1E+300	DM	891.37	-1E+300	0	891.37
RB	0	0.54	0.79	1E+300	Ash	30.1	-1E+300	0	30.10
CRM	0.0598	0.63	0.63	0.66	GE	17.43	-1E+300	0	17.43
SBM	0.2877	1.57	1.59	1.77	CP	187.7	-1E+300	170	187.7
MBM	0	0.42	1.78	1E+300	Fat	85.75	-1E+300	0	85.75
FM	0.0034	1.73	1.78	2.21	Starch	375.15	-1E+300	0	375.15
CM	0.0413	0.34	0.52	0.53	NDF	111.19	-1E+300	0	111.19

BSFL	0	2.33	8.29	1E+300	ADF	47.12	-1E+300	0	47.12
CLM	0	0.65	7.35	1E+300	Ca	5.5	3.34	5.5	8.55
PO	0.06	-8E+14	1.67	1.79	Ca	5.5	5.5	11.8	1E+300
LiSt	0.0114	0.03	0.06	0.92	Mg	1.71	-1E+300	0.5	1.71
CaHPO ₄	0	-2.10	2.52	1E+300	Mg	1.71	1.71	3	1E+300
Ca ₃ (PO ₄) ₂	0	-2.49	7.35	1E+300	K	9	-1E+300	6	9
L-Lys	0.0014	-0.37	6.09	6.66	K	9	8.72	9	9.35
DL-Met	0.0017	0.96	11.79	51.38	Na	1.8	1.76	1.8	2.3
L-Thre	0.0007	0.62	8.39	11.36	Na	1.8	1.8	2.3	1E+300
NaCl	0.004	-1E+300	0.8	0.85	AvP	3.2	-1E+300	3	3.2
Na ₂ CO ₃	0.0001	0.89	0.94	4.19	AvP	3.2	3.12	3.2	3.28
MP	0.01	-1E+300	3.59	1E+300	AMEn	13.2	13.11	13.2	13.32
VP	0.01	-1E+300	1.67	1E+300	Arg	11.48	-1E+300	10.8	11.48
					His	4.38	-1E+300	0	4.38
					Iso	6.87	-1E+300	6.7	6.87
					Leu	13.83	-1E+300	10.6	13.83
					Lys	9.6	8.52	9.6	15.34
					Met	4.2	2.53	4.2	5.69
					Phe	8.17	-1E+300	0	8.17
					Thr	6.4	5.75	6.4	12.49
					Val	7.7	7.53	7.7	7.89
					Ala	8.29	-1E+300	0	8.29
					Asp	10.74	-1E+300	0	10.74
					Cys	2.37	-1E+300	0	2.37
					Glu	15.87	-1E+300	0	15.87
					Gly	7.21	-1E+300	0	7.21
					Pro	9.6	-1E+300	0	9.6
					Ser	8.7	-1E+300	0	8.7
					Tyr	5.72	-1E+300	0	5.72
					Maize	50.88	50.88	70	1E+300
					Wheat	0	0	25	1E+300
					RB	0	0	20	1E+300
					CRM	5.98	5.98	40	1E+300
					SBM	28.77	28.77	30	1E+300
					MBM	0	0	8	1E+300
					FM	0.34	0.34	10	1E+300
					CM	4.13	4.13	20	1E+300
					BSFL	0	0	20	1E+300
					CLM	0	0	20	1E+300
					PO	6	5.41	6	6.44
					LiSt	1.14	1.14	3	1E+300
					CaHPO ₄	0	0	1.5	1E+300
					Ca ₃ (PO ₄) ₂	0	0	1.5	1E+300
					L-Lys	0.14	0.14	0.85	1E+300
					DL-Met	0.17	0.17	0.32	1E+300
					L-Thre	0.07	0.07	0.68	1E+300
					NaCl	0.4	0	0.4	0.41
					Na ₂ CO ₃	0.01	0.01	0.4	1E+300
					MP	1	0.44	1	1.78
					VP	1	0.44	1	1.78

Objective Cost: 1.15/kg

Appendix 6: Result of layer starter 1 at the lower limit energy requirement

Variable	Amount	Valid Cost Range			Constraint	Amount	Valid RHS Range		
		Lower Bound	Current	Upper Range			Lower Bound	Current	Upper Range
Maize	0.0556	0.79	0.86	1.07	Weight	1	0.99	1	1.06
Wheat	0	0.87	11.73	1E+300	DM	891.72	-1E+300	0	891.72
RB	0	0.66	0.79	1E+300	Ash	49.93	-1E+300	0	49.93
CRM	0.4	-3E+13	0.63	0.7	GE	16.86	-1E+300	0	16.86
SBM	0.299	1.38	1.59	2.33	CP	213.60	-1E+300	200	213.6
MBM	0	0.60	1.78	1E+300	Fat	67.34	-1E+300	0	67.34
FM	0.0608	1.56	1.78	2.03	Starch	332.53	-1E+300	0	332.53
CM	0.0977	0.23	0.52	0.56	NDF	107.36	-1E+300	0	107.36
BSFL	0	1.92	8.29	1E+300	ADF	59.22	-1E+300	0	59.22
CLM	0	0.66	7.35	1E+300	Ca	9	4.32	9	10.5
PO	0.05	-7E+15	1.67	1.93	Ca	9	9	10.5	1E+300
LiSt	0.0119	-0.01	0.06	8.63	Mg	1.92	-1E+300	0	1.92
CaHPO ₄	0	-1.13	2.52	1E+300	Mg	1.92	-1E+300	0	1.92
Ca ₃ (PO ₄) ₂	0	-1.31	7.35	1E+300	K	12.42	-1E+300	0	12.42
L-Lys	0.0006	-18.16	6.09	11.41	K	12.42	-1E+300	0	12.42
DL-Met	0.002	1.02	11.79	68.03	Na	1.5	0.77	1.5	1.8
L-Thre	0.0006	0.66	8.39	41.14	Na	1.5	1.5	1.8	1E+300
NaCl	0.0019	-0.01	0.8	0.84	AvP	4.5	-1E+300	4.4	4.5
Na ₂ CO ₃	0	0.89	0.94	1E+300	AvP	4.5	4.48	4.5	4.96
MP	0.01	-1E+300	3.59	1E+300	AMEn	12.13	11.59	12.13	12.47
VP	0.01	-1E+300	1.67	1E+300	Arg	13.31	-1E+300	11.1	13.31
					His	4.52	-1E+300	0	4.52
					Iso	7.5	6.79	7.5	7.51
					Leu	13.11	-1E+300	0	13.11
					Lys	10.7	10.22	10.7	16.62
					Met	4.8	2.86	4.8	5.63
					Phe	8.52	-1E+300	0	8.52
					Thr	6.9	6.27	6.9	12.61
					Val	8.34	-1E+300	7.7	8.34
					Ala	8.50	-1E+300	0	8.5
					Asp	11.78	-1E+300	0	11.78
					Cys	2.08	-1E+300	0	2.08
					Glu	18.05	-1E+300	0	18.05
					Gly	8.56	-1E+300	0	8.56
					Pro	8.72	-1E+300	0	8.72
					Ser	9.15	-1E+300	0	9.15
					Tyr	5.98	-1E+300	0	5.98
					Maize	5.56	5.56	60	1E+300
					Wheat	0	0	20	1E+300
					RB	0	0	10	1E+300
					CRM	40	0	40	41.1
					SBM	29.9	29.9	30	1E+300
					MBM	0	0	6	1E+300
					FM	6.08	6.08	8	1E+300
					CM	9.77	9.77	20	1E+300
					BSFL	0	0	23.93	1E+300
					CLM	0	0	20	1E+300
					PO	5	1.38	5	6.6
					LiSt	1.19	1.19	10	1E+300
					CaHPO ₄	0	0	1.3	1E+300

					Ca ₃ (PO ₄) ₂	0	0	1.3	1E+300
					L-Lys	0.06	0.06	0.8	1E+300
					DL-Met	0.20	0.2	0.28	1E+300
					L-Thre	0.06	0.06	0.64	1E+300
					NaCl	0.19	0.19	0.4	1E+300
					Na ₂ CO ₃	0	0	0.4	1E+300
					MP	1	0	1	1.87
					VP	1	0	1	1.87
Objective Cost: 1.1/kg									

Appendix 7: Layer starter 2 at the lower limit energy requirement

Variable	Amount	Valid Cost Range			Constraint	Amount	Valid RHS Range		
		Lower Bound	Current	Upper Range			Lower Bound	Current	Upper Range
Maize	0.0662	0.79	0.86	1.07	Weight	1	0.95	1	1.03
Wheat	0	0.87	11.73	1E+300	DM	891.65	-1E+300	0	891.65
RB	0	0.66	0.79	1E+300	Ash	49.37	-1E+300	0	49.37
CRM	0.4	-1E+15	0.63	0.7	GE	16.74	-1E+300	0	16.74
SBM	0.2354	1.38	1.59	2.33	CP	195.09	-1E+300	180	195.09
MBM	0	0.60	1.78	1E+300	Fat	66.61	-1E+300	0	66.61
FM	0.0586	1.56	1.78	2.03	Starch	339.06	-1E+300	0	339.06
CM	0.1527	0.23	0.52	0.56	NDF	128.69	-1E+300	0	128.69
BSFL	0	1.92	8.29	1E+300	ADF	67.8	-1E+300	0	67.80
CLM	0	0.66	7.35	1E+300	Ca	9	4.07	9	10.00
PO	0.05	-2E+14	1.67	1.93	Ca	9	9	10	1E+300
LiSt	0.0125	-0.01	0.06	8.63	Mg	1.92	-1E+300	0	1.92
CaHPO ₄	0	-1.13	2.52	1E+300	Mg	1.92	-1E+300	0	1.92
Ca ₃ (PO ₄) ₂	0	-1.31	7.35	1E+300	K	12.47	-1E+300	0	12.47
L-Lys	0.0006	-18.16	6.09	11.41	K	12.47	-1E+300	0	12.47
DL-Met	0.0016	1.02	11.79	68.03	Na	1.5	0.78	1.5	1.80
L-Thre	0.0005	0.66	8.39	41.14	Na	1.5	1.5	1.8	1E+300
NaCl	0.0018	-0.01	0.8	0.84	AvP	4.4	-1E+300	3.9	4.40
Na ₂ CO ₃	0	0.89	0.94	1E+300	AvP	4.4	3.9	4.4	5.39
MP	0.01	-1E+300	3.59	1E+300	AMEn	11.92	11.52	11.92	12.83
VP	0.01	-1E+300	1.67	1E+300	Arg	12.34	-1E+300	9.6	12.34
					His	3.97	-1E+300	0	3.97
					Iso	6.6	5.79	6.6	6.92
					Leu	11.72	-1E+300	0	11.72
					Lys	9.2	8.72	9.2	15.12
					Met	4.2	2.62	4.2	5.39
					Phe	7.58	-1E+300	0	7.58
					Thr	6	5.51	6	11.85
					Val	7.55	-1E+300	6.8	7.55
					Ala	7.66	-1E+300	0	7.66
					Asp	10.44	-1E+300	0	10.44
					Cys	1.84	-1E+300	0	1.84
					Glu	16.66	-1E+300	0	16.66
					Gly	7.74	-1E+300	0	7.74
					Pro	7.61	-1E+300	0	7.61
					Ser	8.02	-1E+300	0	8.02
					Tyr	5.17	-1E+300	0	5.17
					Maize	6.62	6.62	70	1E+300
					Wheat	0	0	25	1E+300
					RB	0	0	20	1E+300

					CRM	40	3.41	40	46.59
					SBM	23.54	23.54	30	1E+300
					MBM	0	0	8	1E+300
					FM	5.86	5.86	10	1E+300
					CM	15.27	15.27	20	1E+300
					BSFL	0	0	23.93	1E+300
					CLM	0	0	20	1E+300
					PO	5	0.11	5	6.76
					LiSt	1.25	1.25	10	1E+300
					CaHPO ₄	0	0	1.3	1E+300
					Ca ₃ (PO ₄) ₂	0	0	1.3	1E+300
					L-Lys	0.06	0.06	0.8	1E+300
					DL-Met	0.16	0.16	0.28	1E+300
					L-Thre	0.05	0.05	0.64	1E+300
					NaCl	0.18	0.18	0.4	1E+300
					Na ₂ CO ₃	0	0	0.4	1E+300
					MP	1	0	1	6.01
					VP	1	0	1	6.01

Objective Cost: 1.03/kg

Appendix 8: Layer grower at the lower limit energy requirement

Variable	Amount	Valid Cost Range			Constraint	Amount	Valid RHS Range		
		Lower Bound	Current	Upper Range			Lower Bound	Current	Upper Range
Maize	0.0635	0.79	0.86	1.07	Weight	1	0.96	1	1
Wheat	0	0.87	11.73	1E+300	DM	891.29	-1E+300	0	891.3
RB	0	0.66	0.79	1E+300	Ash	49.23	-1E+300	0	49.23
CRM	0.4	-8E+13	0.63	0.7	GE	16.69	-1E+300	0	16.69
SBM	0.2018	1.38	1.59	2.33	CP	185.32	-1E+300	170	185.32
MBM	0	0.6	1.78	1E+300	Fat	65.64	-1E+300	0	65.64
FM	0.0534	1.56	1.78	2.03	Starch	337.15	-1E+300	0	337.15
CM	0.1963	0.23	0.52	0.56	NDF	146.39	-1E+300	0	146.39
BSFL	0	1.92	8.29	1E+300	ADF	75.44	-1E+300	0	75.44
CLM	0	0.66	7.35	1E+300	Ca	8	7.15	8	9.5
PO	0.05	-8E+14	1.67	1.93	Ca	8	8	9.5	1E+300
LiSt	0.0107	-0.01	0.06	8.63	Mg	1.9	-1E+300	0	1.90
CaHPO ₄	0	-1.13	2.52	1E+300	Mg	1.9	-1E+300	0	1.90
Ca ₃ (PO ₄) ₂	0	-1.31	7.35	1E+300	K	12.79	-1E+300	0	12.79
L-Lys	0.0005	-18.16	6.09	11.41	K	12.79	-1E+300	0	12.79
DL-Met	0.0015	1.02	11.79	68.03	Na	1.5	0.75	1.5	1.80
L-Thre	0.0004	0.66	8.39	41.14	Na	1.5	1.5	1.8	1E+300
NaCl	0.0019	-0.01	0.8	0.84	AvP	4.3	-1E+300	3.9	4.30
Na ₂ CO ₃	0	0.89	0.94	1E+300	AvP	4.3	3.9	4.3	4.43
MP	0.01	-1E+300	3.59	1E+300	AMEn	11.72	11.69	11.72	12.46
VP	0.01	-1E+300	1.67	1E+300	Arg	11.94	-1E+300	8.5	11.94
					His	3.66	-1E+300	0	3.66
					Iso	6.1	6	6.1	6.36
					Leu	10.93	-1E+300	0	10.93
					Lys	8.2	7.81	8.2	12.29
					Met	3.9	2.46	3.9	4.73
					Phe	7.09	-1E+300	0	7.09
					Thr	5.5	5.07	5.5	10.31
					Val	7.13	-1E+300	6.4	7.13
					Ala	7.11	-1E+300	0	7.11

					Asp	9.73	-1E+300	0	9.73
					Cys	1.70	-1E+300	0	1.70
					Glu	16.08	-1E+300	0	16.08
					Gly	7.18	-1E+300	0	7.18
					Pro	6.94	-1E+300	0	6.94
					Ser	7.37	-1E+300	0	7.37
					Tyr	4.69	-1E+300	0	4.69
					Maize	6.35	6.35	70	1E+300
					Wheat	0	0	25	1E+300
					RB	0	0	20	1E+300
					CRM	40	37.12	40	46.32
					SBM	20.18	20.18	30	1E+300
					MBM	0	0	8	1E+300
					FM	5.34	5.34	10	1E+300
					CM	19.63	19.63	20	1E+300
					BSFL	0	0	23.93	1E+300
					CLM	0	0	20	1E+300
					PO	5	1.01	5	5.14
					LiSt	1.07	1.07	10	1E+300
					CaHPO ₄	0	0	1.3	1E+300
					Ca ₃ (PO ₄) ₂	0	0	1.3	1E+300
					L-Lys	0.05	0.05	0.56	1E+300
					DL-Met	0.15	0.15	0.23	1E+300
					L-Thre	0.04	0.04	0.53	1E+300
					NaCl	0.19	0.19	0.4	1E+300
					Na ₂ CO ₃	0	0	0.4	1E+300
					MP	1	0.78	1	5.09
					VP	1	0.78	1	5.09

Objective Cost: 0.99/kg

Appendix 9: Layer developer at the lower limit energy requirement

Variable	Amount	Valid Cost Range			Constraint	Amount	Valid RHS Range		
		Lower Bound	Current	Upper Range			Lower Bound	Current	Upper Range
Maize	0.1623	0.82	0.86	0.93	Weight	1	1	1	1.04
Wheat	0	0.90	11.73	1E+300	DM	888.16	-1E+300	0	888.16
RB	0	0.68	0.79	1E+300	Ash	44.55	-1E+300	0	44.55
CRM	0.4	-5E+14	0.63	0.72	GE	15.89	-1E+300	0	15.89
SBM	0.1319	1.43	1.59	1.99	CP	155	154.42	155	155.14
MBM	0	0.83	1.78	1E+300	Fat	39.98	-1E+300	0	39.98
FM	0.0453	-1.40	1.78	1.98	Starch	400.46	-1E+300	0	400.46
CM	0.2	-6E+13	0.52	0.76	NDF	150.38	-1E+300	0	150.38
BSFL	0	1.88	8.29	1E+300	ADF	74.3	-1E+300	0	74.3
CLM	0	0.89	7.35	1E+300	Ca	9	-1E+300	8	9
PO	0.0228	1.20	1.67	1.78	Ca	9	8	9	9.76
LiSt	0.0149	-1.61	0.06	0.13	Mg	1.87	-1E+300	0	1.87
CaHPO ₄	0	-1.71	2.52	1E+300	Mg	1.87	-1E+300	0	1.87
Ca ₃ (PO ₄) ₂	0	-2.08	7.35	1E+300	K	11.69	-1E+300	0	11.69
L-Lys	0.00001	-6.70	6.09	31.26	K	11.69	-1E+300	0	11.69
DL-Met	0.0007	2.23	11.79	171.57	Na	1.5	0.69	1.5	1.8
L-Thre	0	2.21	8.39	1E+300	Na	1.5	1.5	1.8	1E+300
NaCl	0.0021	0.13	0.8	0.86	AvP	3.9	-1E+300	3.8	3.9
Na ₂ CO ₃	0	0.88	0.94	1E+300	AvP	3.9	3.8	3.9	4.01
MP	0.01	-1E+300	3.59	1E+300	AMEn	11.3	10.78	11.3	11.37

VP	0.01	-1E+300	1.67	1E+300	Arg	9.91	-1E+300	6.3	9.91
					His	3.03	-1E+300	0	3.03
					Iso	4.92	-1E+300	4.5	4.92
					Leu	9.36	-1E+300	0	9.36
					Lys	6	5.99	6	6.48
					Met	2.8	2.55	2.8	3.78
					Phe	5.84	-1E+300	0	5.84
					Thr	4.12	-1E+300	4.1	4.12
					Val	5.97	-1E+300	4.8	5.97
					Ala	6.17	-1E+300	0	6.17
					Asp	7.86	-1E+300	0	7.86
					Cys	1.46	-1E+300	0	1.46
					Glu	13.42	-1E+300	0	13.42
					Gly	6.08	-1E+300	0	6.08
					Pro	5.91	-1E+300	0	5.91
					Ser	5.99	-1E+300	0	5.99
					Tyr	3.76	-1E+300	0	3.76
					Maize	16.23	16.23	70	1E+300
					Wheat	0	0	25	1E+300
					RB	0	0	20	1E+300
					CRM	40	0	40	40.54
					SBM	13.19	13.19	30	1E+300
					MBM	0	0	8	1E+300
					FM	4.53	4.53	10	1E+300
					CM	20	19.88	20	20.58
					BSFL	0	0	23.93	1E+300
					CLM	0	0	20	1E+300
					PO	2.28	2.28	5	1E+300
					LiSt	1.49	1.49	10	1E+300
					CaHPO ₄	0	0	1.3	1E+300
					Ca ₃ (PO ₄) ₂	0	0	1.3	1E+300
					L-Lys	0.001	0.001	0.42	1E+300
					DL-Met	0.07	0.07	0.19	1E+300
					L-Thre	0	0	0.35	1E+300
					NaCl	0.21	0.21	0.4	1E+300
					Na ₂ CO ₃	0	0	0.4	1E+300
					MP	1	0	1	1.2
					VP	1	0	1	1.2

Objective Cost: 0.89/kg

Appendix 10: Layer pre-lay at the lower limit energy requirement

Variable	Amount	Valid Cost Range			Constraint	Amount	Valid RHS Range		
		Lower Bound	Current	Upper Range			Lower Bound	Current	Upper Range
Maize	0.0678	0.79	0.86	1.07	Weight	1	1	1	1
Wheat	0	0.87	11.73	1E+300	DM	893.95	-1E+300	0	893.95
RB	0	0.66	0.79	1E+300	Ash	48.31	-1E+300	0	48.31
CRM	0.4	-4E+31	0.63	0.7	GE	16.24	-1E+300	0	16.24
SBM	0.1665	1.38	1.59	2.33	CP	172.73	-1E+300	165	172.73
MBM	0	0.6	1.78	1E+300	Fat	65.76	-1E+300	0	65.76
FM	0.0607	1.56	1.78	2.03	Starch	339.66	-1E+300	0	339.66
CM	0.1954	0.23	0.52	0.56	NDF	142.22	-1E+300	0	142.22
BSFL	0	1.92	8.29	1E+300	ADF	72.87	-1E+300	0	72.87
CLM	0	0.66	7.35	1E+300	Ca	18	16.96	18	18.2

PO	0.05	-1E+15	1.67	1.93	Ca	18	18	25	1E+300
LiSt	0.0364	-0.01	0.06	8.63	Mg	2.35	-1E+300	0	2.35
CaHPO ₄	0	-1.13	2.52	1E+300	Mg	2.35	-1E+300	0	2.35
Ca ₃ (PO ₄) ₂	0	-1.31	7.35	1E+300	K	12.14	-1E+300	0	12.14
L-Lys	0.00001	-18.16	6.09	11.41	K	12.14	-1E+300	0	12.14
DL-Met	0.0012	1.02	11.79	68.03	Na	1.5	0.84	1.5	1.7
L-Thre	0.0003	0.66	8.39	41.14	Na	1.5	1.5	1.8	1E+300
NaCl	0.0017	-0.01	0.8	0.84	AvP	4.3	-1E+300	4.2	4.3
Na ₂ CO ₃	0	0.89	0.94	1E+300	AvP	4.3	4.2	4.3	4.32
MP	0.01	-1E+300	3.59	1E+300	AMEn	11.51	11.47	11.51	11.52
VP	0.01	-1E+300	1.67	1E+300	Arg	11.06	-1E+300	7.5	11.06
					His	3.37	-1E+300	0	3.37
					Iso	5.6	5.48	5.6	5.6
					Leu	10.11	-1E+300	0	10.11
					Lys	7.2	7.2	7.2	10.56
					Met	3.5	2.36	3.5	4.24
					Phe	6.5	-1E+300	0	6.5
					Thr	5	4.69	5	6.65
					Val	6.63	-1E+300	6.1	6.63
					Ala	6.77	-1E+300	0	6.77
					Asp	8.89	-1E+300	0	8.89
					Cys	1.55	-1E+300	0	1.55
					Glu	14.88	-1E+300	0	14.88
					Gly	6.93	-1E+300	0	6.93
					Pro	6.39	-1E+300	0	6.39
					Ser	6.77	-1E+300	0	6.77
					Tyr	4.29	-1E+300	0	4.29
					Maize	6.78	6.78	70	1E+300
					Wheat	0	0	25	1E+300
					RB	0	0	20	1E+300
					CRM	40	36.46	40	40.21
					SBM	16.65	16.65	30	1E+300
					MBM	0	0	8	1E+300
					FM	6.07	6.07	10	1E+300
					CM	19.54	19.54	20	1E+300
					BSFL	0	0	23.93	1E+300
					CLM	0	0	20	1E+300
					PO	5	4.95	5	5.17
					LiSt	3.64	3.64	10	1E+300
					CaHPO ₄	0	0	1.3	1E+300
					Ca ₃ (PO ₄) ₂	0	0	1.3	1E+300
					L-Lys	0.0006	0.0006	0.42	1E+300
					DL-Met	0.12	0.12	0.19	1E+300
					L-Thre	0.03	0.03	0.35	1E+300
					NaCl	0.17	0.17	0.4	1E+300
					Na ₂ CO ₃	0	0	0.4	1E+300
					MP	1	0.73	1	1.05
					VP	1	0.73	1	1.05

Objective Cost: 0.94/kg

Appendix 11: Layer peaking at the lower limit energy requirement

Variable	Amount	Valid Cost Range			Constraint	Amount	Valid RHS Range		
		Lower Bound	Current	Upper Range			Lower Bound	Current	Upper Range
Maize	0.5901	-7.76	0.86	2.49	Weight	1	0.99	1	1.02
Wheat	0	0.86	11.73	1E+300	DM	900.62	-1E+300	0	900.62
RB	0	-1.65	0.79	1E+300	Ash	35.07	-1E+300	0	35.07
CRM	0	-1.14	0.63	1E+300	GE	16.62	-1E+300	0	16.62
SBM	0.1211	-5.2	1.59	4.28	CP	180.68	-1E+300	178	180.68
MBM	0	1.01	1.78	1E+300	Fat	89.76	-1E+300	0	89.76
FM	0.0412	-5.48	1.78	4.45	Starch	383.20	-1E+300	0	383.2
CM	0	-4.07	0.52	1E+300	NDF	99.53	-1E+300	0	99.53
BSFL	0.104	2.21	8.29	23.01	ADF	38.83	-1E+300	0	38.83
CLM	0	-3.96	7.35	1E+300	Ca	33.3	24.99	33.3	36.67
PO	0.05	-1E+300	1.67	19.56	Ca	33.3	33.3	44.4	1E+300
LiSt	0.0704	-17.28	0.06	3.28	Mg	2.82	-1E+300	0	2.82
CaHPO ₄	0	-3.54	2.52	1E+300	Mg	2.82	-1E+300	0	2.82
Ca ₃ (PO ₄) ₂	0	0.98	7.35	1E+300	K	5.71	-1E+300	0	5.71
L-Lys	0	-424.46	6.09	1E+300	K	5.71	-1E+300	0	5.71
DL-Met	0.0012	4.24	11.79	703.52	Na	1.6	0.71	1.6	2
L-Thre	0.00003	-1.77	8.39	1323.19	Na	1.6	1.6	2	1E+300
NaCl	0	-0.35	0.8	1E+300	AvP	3.82	-1E+300	3.6	3.82
Na ₂ CO ₃	0.002	-13.08	0.94	2.22	AvP	3.82	3.82	4.8	1E+300
MP	0.01	-1E+300	3.59	1E+300	AMEn	13.2	12.98	13.2	13.3
VP	0.01	-1E+300	1.67	1E+300	Arg	9.24	-1E+300	8.6	9.24
					His	3.99	-1E+300	0	3.99
					Iso	6.6	6.4	6.6	6.65
					Leu	13.50	-1E+300	0	13.5
					Lys	8.3	8.19	8.3	8.41
					Met	4.2	2.98	4.2	5.05
					Phe	7.16	-1E+300	0	7.16
					Thr	5.8	5.77	5.8	10.13
					Val	8.15	-1E+300	7.3	8.15
					Ala	9.88	-1E+300	0	9.88
					Asp	10.58	-1E+300	0	10.58
					Cys	1.87	-1E+300	0	1.87
					Glu	14.39	-1E+300	0	14.39
					Gly	8.69	-1E+300	0	8.69
					Pro	10.09	-1E+300	0	10.09
					Ser	7.90	-1E+300	0	7.9
					Tyr	6.82	-1E+300	0	6.82
					Maize	59.01	59.01	70	1E+300
					Wheat	0	0	25	1E+300
					RB	0	0	25	1E+300
					CRM	0	0	40	1E+300
					SBM	12.11	12.11	30	1E+300
					MBM	0	0	8	1E+300
					FM	4.12	4.12	10	1E+300
					CM	0	0	20	1E+300
					BSFL	10.4	10.4	23.93	1E+300
					CLM	0	0	20	1E+300
					PO	5	4.6	5	5.81
					LiSt	7.04	7.04	10	1E+300
					CaHPO ₄	0	0	1.3	1E+300

					Ca ₃ (PO ₄) ₂	0	0	1.3	1E+300
					L-Lys	0	0	0.49	1E+300
					DL-Met	0.12	0.12	0.21	1E+300
					L-Thre	0.003	0.003	0.44	1E+300
					NaCl	0	0	0.4	1E+300
					Na ₂ CO ₃	0.2	0.2	0.4	1E+300
					MP	1	0	1	1.89
					VP	1	0	1	1.89
Objective Cost: 1.79/kg									

Appendix 12: Layer phase 2 at the lower limit energy requirement

Variable	Amount	Valid Cost Range			Constraint	Amount	Valid RHS Range		
		Lower Bound	Current	Upper Range			Lower Bound	Current	Upper Range
Maize	0.617	-7.76	0.86	2.49	Weight	1	1	1	1.01
Wheat	0	0.86	11.73	1E+300	DM	899.59	-1E+300	0	899.59
RB	0	-1.65	0.79	1E+300	Ash	29.72	-1E+300	0	29.72
CRM	0	-1.14	0.63	1E+300	GE	16.29	-1E+300	0	16.29
SBM	0.1394	-5.2	1.59	4.28	CP	162.16	-1E+300	160	162.16
MBM	0	1.01	1.78	1E+300	Fat	85.14	-1E+300	0	85.14
FM	0.0362	-5.48	1.78	4.45	Starch	400.34	-1E+300	0	400.34
CM	0	-4.07	0.52	1E+300	NDF	93.53	-1E+300	0	93.53
BSFL	0.0539	2.21	8.29	23.01	ADF	34.82	-1E+300	0	34.82
CLM	0	-3.96	7.35	1E+300	Ca	35	30.05	35	39.57
PO	0.05	-3E+17	1.67	19.56	Ca	35	35	42	1E+300
LiSt	0.0806	-17.28	0.06	3.28	Mg	2.92	-1E+300	0	2.92
CaHPO ₄	0	-3.54	2.52	1E+300	Mg	2.92	-1E+300	0	2.92
Ca ₃ (PO ₄) ₂	0	0.98	7.35	1E+300	K	5.66	-1E+300	0	5.66
L-Lys	0	-424.46	6.09	1E+300	K	5.66	-1E+300	0	5.66
DL-Met	0.0011	4.24	11.79	703.52	Na	1.4	0.61	1.4	1.7
L-Thre	0.00004	-1.77	8.39	1323.19	Na	1.4	1.4	1.7	1E+300
NaCl	0	-0.35	0.8	1E+300	AvP	3.53	-1E+300	3.4	3.53
Na ₂ CO ₃	0.0018	-13.08	0.94	2.22	AvP	3.53	3.53	4.1	1E+300
MP	0.01	-1E+300	3.59	1E+300	AMEn	13	12.87	13	13.14
VP	0.01	-1E+300	1.67	1E+300	Arg	8.61	-1E+300	7.7	8.61
					His	3.72	-1E+300	0	3.72
					Iso	5.9	5.74	5.9	5.96
					Leu	12.53	-1E+300	0	12.53
					Lys	7.4	7.33	7.4	7.55
					Met	3.7	2.64	3.7	5.59
					Phe	6.65	-1E+300	0	6.65
					Thr	5.2	5.17	5.2	9.82
					Val	7.09	-1E+300	6.5	7.09
					Ala	8.73	-1E+300	0	8.73
					Asp	9.2	-1E+300	0	9.2
					Cys	1.89	-1E+300	0	1.89
					Glu	12.83	-1E+300	0	12.83
					Gly	7.68	-1E+300	0	7.68
					Pro	9.2	-1E+300	0	9.2
					Ser	7.34	-1E+300	0	7.34
					Tyr	5.67	-1E+300	0	5.67
					Maize	61.7	61.7	70	1E+300
					Wheat	0	0	25	1E+300
					RB	0	0	25	1E+300

					CRM	0	0	40	1E+300
					SBM	13.94	13.94	30	1E+300
					MBM	0	0	8	1E+300
					FM	3.62	3.62	10	1E+300
					CM	0	0	20	1E+300
					BSFL	5.39	5.39	23.93	1E+300
					CLM	0	0	20	1E+300
					PO	5	4.46	5	5.48
					LiSt	8.06	8.06	10	1E+300
					CaHPO ₄	0	0	1.3	1E+300
					Ca ₃ (PO ₄) ₂	0	0	1.3	1E+300
					L-Lys	0	0	0.69	1E+300
					DL-Met	0.11	0.11	0.3	1E+300
					L-Thre	0.004	0.004	0.47	1E+300
					NaCl	0	0	0.4	1E+300
					Na ₂ CO ₃	0.18	0.18	0.4	1E+300
					MP	1	0	1	2.2
					VP	1	0	1	2.2

Objective Cost: 1.42/kg

Appendix 13: Layer phase 3 at the lower limit energy requirement

Variable	Amount	Valid Cost Range			Constraint	Amount	Valid RHS Range		
		Lower Bound	Current	Upper Range			Lower Bound	Current	Upper Range
Maize	0.6169	-7.76	0.86	2.49	Weight	1	0.98	1	1.02
Wheat	0	0.86	11.73	1E+300	DM	899.28	-1E+300	0	899.28
RB	0	-1.65	0.79	1E+300	Ash	26.76	-1E+300	0	26.76
CRM	0	-1.14	0.63	1E+300	GE	16.08	-1E+300	0	16.08
SBM	0.164	-5.20	1.59	4.28	CP	155.79	-1E+300	151.8	155.79
MBM	0	1.01	1.78	1E+300	Fat	82.17	-1E+300	0	82.17
FM	0.0264	-5.48	1.78	4.45	Starch	400.28	-1E+300	0	400.28
CM	0	-4.07	0.52	1E+300	NDF	91.41	-1E+300	0	91.41
BSFL	0.0311	2.21	8.29	23.01	ADF	33.76	-1E+300	0	33.76
CLM	0	-3.96	7.35	1E+300	Ca	36.7	30.89	36.7	42.58
PO	0.05	-2E+16	1.67	19.56	Ca	36.7	36.7	44	1E+300
LiSt	0.0885	-17.28	0.06	3.28	Mg	3.06	-1E+300	0	3.06
CaHPO ₄	0	-3.54	2.52	1E+300	Mg	3.06	-1E+300	0	3.06
Ca ₃ (PO ₄) ₂	0	0.98	7.35	1E+300	K	5.87	-1E+300	0	5.87
L-Lys	0	-424.46	6.09	1E+300	K	5.87	-1E+300	0	5.87
DL-Met	0.0011	4.24	11.79	703.52	Na	1.4	0.48	1.4	1.70
L-Thre	0.00005	-1.77	8.39	1323.19	Na	1.4	1.4	1.7	1E+300
NaCl	0	-0.35	0.8	1E+300	AvP	3.26	-1E+300	3.1	3.26
Na ₂ CO ₃	0.0021	-13.08	0.94	2.22	AvP	3.26	3.26	3.7	1E+300
MP	0.01	-1E+300	3.59	1E+300	AMEn	12.8	12.64	12.8	12.98
VP	0.01	-1E+300	1.67	1E+300	Arg	8.56	-1E+300	7.4	8.56
					His	3.67	-1E+300	0	3.67
					Iso	5.7	5.51	5.7	5.77
					Leu	12.22	-1E+300	0	12.22
					Lys	7.1	7.02	7.1	7.3
					Met	3.5	2.45	3.5	5.41
					Phe	6.58	-1E+300	0	6.58
					Thr	5	4.96	5	9.61
					Val	6.7	-1E+300	6.2	6.7
					Ala	8.16	-1E+300	0	8.16

					Asp	8.81	-1E+300	0	8.81
					Cys	1.94	-1E+300	0	1.94
					Glu	12.45	-1E+300	0	12.45
					Gly	7.1	-1E+300	0	7.1
					Pro	8.87	-1E+300	0	8.87
					Ser	7.21	-1E+300	0	7.21
					Tyr	5.24	-1E+300	0	5.24
					Maize	61.69	61.69	70	1E+300
					Wheat	0	0	25	1E+300
					RB	0	0	25	1E+300
					CRM	0	0	40	1E+300
					SBM	16.4	16.4	30	1E+300
					MBM	0	0	8	1E+300
					FM	2.64	2.64	10	1E+300
					CM	0	0	20	1E+300
					BSFL	3.11	3.11	23.93	1E+300
					CLM	0	0	20	1E+300
					PO	5	4.3	5	5.58
					LiSt	8.85	8.85	10	1E+300
					CaHPO ₄	0	0	1.3	1E+300
					Ca ₃ (PO ₄) ₂	0	0	1.3	1E+300
					L-Lys	0	0	0.69	1E+300
					DL-Met	0.11	0.11	0.3	1E+300
					L-Thre	0.005	0.005	0.47	1E+300
					NaCl	0	0	0.4	1E+300
					Na ₂ CO ₃	0.21	0.21	0.4	1E+300
					MP	1	0	1	2.55
					VP	1	0	1	2.55

Objective Cost: 1.25/kg

Appendix 14: Layer phase 4 at the lower limit energy requirement

Variable	Amount	Valid Cost Range			Constraint	Amount	Valid RHS Range		
		Lower Bound	Current	Upper Range			Lower Bound	Current	Upper Range
Maize	0.6178	0.7	0.86	0.87	Weight	1	1	1	1
Wheat	0	0.89	11.73	1E+300	DM	899	-1E+300	0	899
RB	0	0.68	0.79	1E+300	Ash	25.67	-1E+300	0	25.67
CRM	0	0.62	0.63	1E+300	GE	15.89	-1E+300	0	15.89
SBM	0.1707	1.57	1.59	1.65	CP	149.46	-1E+300	148.2	149.46
MBM	0	1.01	1.78	1E+300	Fat	79.78	-1E+300	0	79.78
FM	0.034	1.68	1.78	1.82	Starch	400.7	-1E+300	0	400.7
CM	0.0093	0.48	0.52	0.55	NDF	90.19	-1E+300	0	90.19
BSFL	0	2.14	8.29	1E+300	ADF	32.64	-1E+300	0	32.64
CLM	0	0.53	7.35	1E+300	Ca	38.3	36.91	38.3	39.61
PO	0.05	-5E+15	1.67	2.31	Ca	38.3	38.3	46	1E+300
LiSt	0.0949	-0.31	0.06	1.95	Mg	3.15	-1E+300	0	3.15
CaHPO ₄	0	-0.05	2.52	1E+300	Mg	3.15	-1E+300	0	3.15
Ca ₃ (PO ₄) ₂	0	0.17	7.35	1E+300	K	6.011	-1E+300	0	6.01
L-Lys	0	-22.96	6.09	1E+300	K	6.011	-1E+300	0	6.01
DL-Met	0.0011	7.48	11.79	23.66	Na	1.4	0.57	1.4	1.7
L-Thre	0	0.55	8.39	1E+300	Na	1.4	1.4	1.7	1E+300
NaCl	0.0022	-0.32	0.8	0.81	AvP	3.37	-1E+300	2.9	3.37
Na ₂ CO ₃	0	0.93	0.94	1E+300	AvP	3.37	3.37	3.5	1E+300
MP	0.01	-1E+300	3.59	1E+300	AMEn	12.6	12.53	12.6	12.65

VP	0.01	-1E+300	1.67	1E+300	Arg	8.47	-1E+300	7	8.47
					His	3.56	-1E+300	0	3.56
					Iso	5.4	5.38	5.4	5.45
					Leu	11.8	-1E+300	0	11.8
					Lys	6.8	6.78	6.8	6.83
					Met	3.4	2.35	3.4	5.32
					Phe	6.38	-1E+300	0	6.38
					Thr	4.71	-1E+300	4.7	4.71
					Val	6.23	-1E+300	6	6.23
					Ala	7.7	-1E+300	0	7.7
					Asp	8.13	-1E+300	0	8.13
					Cys	1.95	-1E+300	0	1.95
					Glu	11.84	-1E+300	0	11.84
					Gly	6.85	-1E+300	0	6.85
					Pro	8.41	-1E+300	0	8.41
					Ser	7.02	-1E+300	0	7.02
					Tyr	4.62	-1E+300	0	4.62
					Maize	61.78	61.78	70	1E+300
					Wheat	0	0	25	1E+300
					RB	0	0	25	1E+300
					CRM	0	0	40	1E+300
					SBM	17.07	17.07	30	1E+300
					MBM	0	0	8	1E+300
					FM	3.4	3.4	10	1E+300
					CM	0.93	0.93	20	1E+300
					BSFL	0	0	23.93	1E+300
					CLM	0	0	20	1E+300
					PO	5	4.75	5	5.36
					LiSt	9.49	9.49	10	1E+300
					CaHPO ₄	0	0	1.3	1E+300
					Ca ₃ (PO ₄) ₂	0	0	1.3	1E+300
					L-Lys	0	0	0.69	1E+300
					DL-Met	0.11	0.11	0.3	1E+300
					L-Thre	0	0	0.47	1E+300
					NaCl	0.22	0.22	0.4	1E+300
					Na ₂ CO ₃	0	0	0.4	1E+300
					MP	1	0.63	1	1.34
					VP	1	0.63	1	1.34

Objective Cost: 1.02/kg

Appendix 15: Layer phase 5 at the lower limit energy requirement

Variable	Amount	Valid Cost Range			Constraint	Amount	Valid RHS Range		
		Lower Bound	Current	Upper Range			Lower Bound	Current	Upper Range
Maize	0.5982	0.79	0.86	0.88	Weight	1	0.99	1	1.09
Wheat	0	0.89	11.73	1E+300	DM	899.19	-1E+300	0	899.19
RB	0	0.68	0.79	1E+300	Ash	24.95	-1E+300	0	24.95
CRM	0.0325	0.61	0.63	0.7	GE	15.78	-1E+300	0	15.78
SBM	0.1599	1.55	1.59	2.33	CP	141.65	-1E+300	140.9	141.65
MBM	0	0.91	1.78	1E+300	Fat	78.69	-1E+300	0	78.69
FM	0.0312	-3.18	1.78	1.85	Starch	411.8	-1E+300	0	411.8
CM	0.0073	0.35	0.52	0.58	NDF	87.16	-1E+300	0	87.16
BSFL	0	2.1	8.29	1E+300	ADF	31.94	-1E+300	0	31.94
CLM	0	0.56	7.35	1E+300	Ca	39.2	5.38	39.2	40.11

PO	0.05	-2E+15	1.67	2.23	Ca	39.2	39.2	47	1E+300
LiSt	0.0976	-0.29	0.06	10.2	Mg	3.17	-1E+300	0	3.17
CaHPO ₄	0	-0.31	2.52	1E+300	Mg	3.17	-1E+300	0	3.17
Ca ₃ (PO ₄) ₂	0	-0.18	7.35	1E+300	K	5.92	-1E+300	0	5.92
L-Lys	0	-18.16	6.09	1E+300	K	5.92	-1E+300	0	5.92
DL-Met	0.001	4.76	11.79	142.54	Na	1.4	0.51	1.4	1.7
L-Thre	0.00005	0.57	8.39	113.59	Na	1.4	1.4	1.7	1E+300
NaCl	0.0023	-0.29	0.8	0.82	AvP	3.2	-1E+300	2.7	3.20
Na ₂ CO ₃	0	0.92	0.94	1E+300	AvP	3.2	3.09	3.2	3.48
MP	0.01	-1E+300	3.59	1E+300	AMEn	12.6	10.98	12.6	12.68
VP	0.01	-1E+300	1.67	1E+300	Arg	7.97	-1E+300	6.6	7.97
					His	3.38	-1E+300	0	3.38
					Iso	5.1	5.07	5.1	5.15
					Leu	11.21	-1E+300	0	11.21
					Lys	6.4	6.32	6.4	6.53
					Met	3.2	2.23	3.2	5.19
					Phe	6.04	-1E+300	0	6.04
					Thr	4.5	4.45	4.5	9.11
					Val	5.89	-1E+300	5.6	5.89
					Ala	7.31	-1E+300	0	7.31
					Asp	7.68	-1E+300	0	7.68
					Cys	1.86	-1E+300	0	1.86
					Glu	11.18	-1E+300	0	11.18
					Gly	6.47	-1E+300	0	6.47
					Pro	8	-1E+300	0	8
					Ser	6.64	-1E+300	0	6.64
					Tyr	4.37	-1E+300	0	4.37
					Maize	59.82	59.82	70	1E+300
					Wheat	0	0	25	1E+300
					RB	0	0	25	1E+300
					CRM	3.25	3.25	40	1E+300
					SBM	15.99	15.99	30	1E+300
					MBM	0	0	8	1E+300
					FM	3.12	3.12	10	1E+300
					CM	0.73	0.73	20	1E+300
					BSFL	0	0	23.93	1E+300
					CLM	0	0	20	1E+300
					PO	5	4.66	5	12.74
					LiSt	9.76	9.76	10	1E+300
					CaHPO ₄	0	0	1.3	1E+300
					Ca ₃ (PO ₄) ₂	0	0	1.3	1E+300
					L-Lys	0	0	0.69	1E+300
					DL-Met	0.1	0.10	0.3	1E+300
					L-Thre	0.005	0.005	0.47	1E+300
					NaCl	0.23	0.23	0.4	1E+300
					Na ₂ CO ₃	0	0	0.4	1E+300
					MP	1	0	1	1.64
					VP	1	0	1	1.64

Objective Cost: 1/kg

Appendix 16: Layer starter 1 at the upper limit energy requirement

Variable	Amount	Valid Cost Range			Constraint	Amount	Valid RHS Range		
		Lower Bound	Current	Upper Range			Lower Bound	Current	Upper Range
Maize	0.1582	0.79	0.86	1.11	Weight	1	1	1	1.01
Wheat	0	0.92	11.73	1E+300	DM	891.85	-1E+300	0	891.85
RB	0	0.21	0.79	1E+300	Ash	46.19	-1E+300	0	46.19
CRM	0.3839	0.32	0.63	0.7	GE	17	-1E+300	0	17
SBM	0.3	-1E+15	1.59	2.33	CP	207.1	-1E+300	200	207.1
MBM	0	-0.81	1.78	1E+300	Fat	71.46	-1E+300	0	71.46
FM	0.0729	1.10	1.78	2.46	Starch	386.73	-1E+300	0	386.73
CM	0.0002	0.26	0.52	0.61	NDF	68.49	-1E+300	0	68.49
BSFL	0	2.76	8.29	1E+300	ADF	39.22	-1E+300	0	39.22
CLM	0	0.73	7.35	1E+300	Ca	9	4.9	9	9.06
PO	0.05	-4E+15	1.67	1.93	Ca	9	9	10.5	1E+300
LiSt	0.0106	-0.09	0.06	8.27	Mg	1.71	-1E+300	0	1.71
CaHPO ₄	0	-5.38	2.52	1E+300	Mg	1.71	-1E+300	0	1.71
Ca ₃ (PO ₄) ₂	0	-6.50	7.35	1E+300	K	10.36	-1E+300	0	10.36
L-Lys	0.0001	-18.16	6.09	24.41	K	10.36	-1E+300	0	10.36
DL-Met	0.0019	0.98	11.79	106.21	Na	1.5	0.84	1.5	1.56
L-Thre	0.0005	0.60	8.39	79.4	Na	1.5	1.5	1.8	1E+300
NaCl	0.0017	-0.09	0.8	0.84	AvP	4.5	-1E+300	4.4	4.50
Na ₂ CO ₃	0	0.90	0.94	1E+300	AvP	4.5	4.4	4.5	4.51
MP	0.01	-1E+300	3.59	1E+300	AMEn	12.97	12.47	12.97	12.97
VP	0.01	-1E+300	1.67	1E+300	Arg	12.21	-1E+300	11.1	12.21
					His	4.61	-1E+300	0	4.61
					Iso	7.5	7.5	7.5	7.98
					Leu	13.42	-1E+300	0	13.42
					Lys	10.7	10.62	10.7	17.01
					Met	4.8	4.47	4.8	5.72
					Phe	8.38	-1E+300	0	8.38
					Thr	6.9	6.4	6.9	10.06
					Val	8.19	-1E+300	7.7	8.19
					Ala	8.98	-1E+300	0	8.98
					Asp	11.53	-1E+300	0	11.53
					Cys	2.13	-1E+300	0	2.13
					Glu	16.74	-1E+300	0	16.74
					Gly	8.98	-1E+300	0	8.98
					Pro	9.29	-1E+300	0	9.29
					Ser	9.29	-1E+300	0	9.29
					Tyr	6.17	-1E+300	0	6.17
					Maize	15.82	15.82	60	1E+300
					Wheat	0	0	20	1E+300
					RB	0	0	10	1E+300
					CRM	38.39	38.39	40	1E+300
					SBM	30	26.38	30	30.02
					MBM	0	0	6	1E+300
					FM	7.29	7.29	8	1E+300
					CM	0.02	0.02	20	1E+300
					BSFL	0	0	23.93	1E+300
					CLM	0	0	20	1E+300
					PO	5	4.99	5	9.65
					LiSt	1.06	1.06	10	1E+300
					CaHPO ₄	0	0	1.3	1E+300

					Ca ₃ (PO ₄) ₂	0	0	1.3	1E+300
					L-Lys	0.01	0.01	0.8	1E+300
					DL-Met	0.19	0.19	0.28	1E+300
					L-Thre	0.05	0.05	0.64	1E+300
					NaCl	0.17	0.17	0.4	1E+300
					Na ₂ CO ₃	0	0	0.4	1E+300
					MP	1	0	1	1.02
					VP	1	0	1	1.02
Objective Cost: 1.15/kg									

Appendix 17: Layer starter 2 at the upper limit energy requirement

Variable	Amount	Valid Cost Range			Constraint	Amount	Valid RHS Range		
		Lower Bound	Current	Upper Range			Lower Bound	Current	Upper Range
Maize	0.1527	0.79	0.86	1.07	Weight	1	1	1	1.09
Wheat	0	0.87	11.73	1E+300	DM	891.79	-1E+300	0	891.79
RB	0	0.66	0.79	1E+300	Ash	46	-1E+300	0	46
CRM	0.4	-9E+14	0.63	0.7	GE	16.86	-1E+300	0	16.86
SBM	0.238	1.38	1.59	2.33	CP	188.51	-1E+300	180	188.51
MBM	0	0.60	1.78	1E+300	Fat	70.32	-1E+300	0	70.32
FM	0.0716	1.56	1.78	2.03	Starch	394.65	-1E+300	0	394.65
CM	0.0532	0.23	0.52	0.56	NDF	87.91	-1E+300	0	87.91
BSFL	0	1.92	8.29	1E+300	ADF	47.49	-1E+300	0	47.49
CLM	0	0.66	7.35	1E+300	Ca	9	4.66	9	10
PO	0.05	-1E+300	1.67	1.93	Ca	9	9	10	1E+300
LiSt	0.011	-0.01	0.06	8.63	Mg	1.7	-1E+300	0	1.7
CaHPO ₄	0	-1.13	2.52	1E+300	Mg	1.7	-1E+300	0	1.7
Ca ₃ (PO ₄) ₂	0	-1.31	7.35	1E+300	K	10.47	-1E+300	0	10.47
L-Lys	0.00005	-18.16	6.09	11.41	K	10.47	-1E+300	0	10.47
DL-Met	0.0015	1.02	11.79	68.03	Na	1.5	0.86	1.5	1.8
L-Thre	0.0004	0.66	8.39	41.14	Na	1.5	1.5	1.8	1E+300
NaCl	0.0016	-0.01	0.8	0.84	AvP	4.4	-1E+300	3.9	4.4
Na ₂ CO ₃	0	0.89	0.94	1E+300	AvP	4.4	3.9	4.4	4.54
MP	0.01	-1E+300	3.59	1E+300	AMEn	12.76	11.52	12.76	12.83
VP	0.01	-1E+300	1.67	1E+300	Arg	11.22	-1E+300	9.6	11.22
					His	4.06	-1E+300	0	4.06
					Iso	6.6	6.14	6.6	6.63
					Leu	11.96	-1E+300	0	11.96
					Lys	9.2	9.16	9.2	15.56
					Met	4.2	2.7	4.2	5.47
					Phe	7.43	-1E+300	0	7.43
					Thr	6	5.64	6	11.97
					Val	7.38	-1E+300	6.8	7.38
					Ala	8.11	-1E+300	0	8.11
					Asp	10.18	-1E+300	0	10.18
					Cys	1.87	-1E+300	0	1.87
					Glu	15.34	-1E+300	0	15.34
					Gly	8.16	-1E+300	0	8.16
					Pro	8.14	-1E+300	0	8.14
					Ser	8.15	-1E+300	0	8.15
					Tyr	5.35	-1E+300	0	5.35
					Maize	15.27	15.27	70	1E+300
					Wheat	0	0	25	1E+300
					RB	0	0	20	1E+300

					CRM	40	0	40	41.65
					SBM	23.8	23.8	30	1E+300
					MBM	0	0	8	1E+300
					FM	7.16	7.16	10	1E+300
					CM	5.32	5.32	20	1E+300
					BSFL	0	0	23.93	1E+300
					CLM	0	0	20	1E+300
					PO	5	4.61	5	9.39
					LiSt	1.1	1.1	10	1E+300
					CaHPO ₄	0	0	1.3	1E+300
					Ca ₃ (PO ₄) ₂	0	0	1.3	1E+300
					L-Lys	0.005	0.005	0.8	1E+300
					DL-Met	0.15	0.15	0.28	1E+300
					L-Thre	0.04	0.04	0.64	1E+300
					NaCl	0.16	0.16	0.4	1E+300
					Na ₂ CO ₃	0	0	0.4	1E+300
					MP	1	0	1	1.4
					VP	1	0	1	1.4

Objective Cost: 1.08/kg

Appendix 18: Layer grower at the upper limit energy requirement

Variable	Amount	Valid Cost Range			Constraint	Amount	Valid RHS Range		
		Lower Bound	Current	Upper Range			Lower Bound	Current	Upper Range
Maize	0.1683	0.79	0.86	0.88	Weight	1	0.91	1	1
Wheat	0	0.89	11.73	1E+300	DM	891.42	-1E+300	0	891.42
RB	0	0.68	0.79	1E+300	Ash	45.46	-1E+300	0	45.46
CRM	0.3807	0.61	0.63	0.7	GE	16.83	-1E+300	0	16.83
SBM	0.2025	1.55	1.59	2.33	CP	178.91	-1E+300	170	178.91
MBM	0	0.91	1.78	1E+300	Fat	69.79	-1E+300	0	69.79
FM	0.0652	-3.18	1.78	1.85	Starch	390.42	-1E+300	0	390.42
CM	0.1004	0.35	0.52	0.58	NDF	108.37	-1E+300	0	108.37
BSFL	0	2.10	8.29	1E+300	ADF	55.74	-1E+300	0	55.74
CLM	0	0.56	7.35	1E+300	Ca	8	6.23	8	9.5
PO	0.05	-2E+15	1.67	2.23	Ca	8	8	9.5	1E+300
LiSt	0.0094	-0.29	0.06	10.2	Mg	1.69	-1E+300	0	1.69
CaHPO ₄	0	-0.31	2.52	1E+300	Mg	1.69	-1E+300	0	1.69
Ca ₃ (PO ₄) ₂	0	-0.18	7.35	1E+300	K	10.74	-1E+300	0	10.74
L-Lys	0	-18.16	6.09	1E+300	K	10.74	-1E+300	0	10.74
DL-Met	0.0014	4.76	11.79	142.54	Na	1.5	0.83	1.5	1.8
L-Thre	0.0003	0.57	8.39	113.59	Na	1.5	1.5	1.8	1E+300
NaCl	0.0017	-0.29	0.8	0.82	AvP	4.3	-1E+300	3.9	4.3
Na ₂ CO ₃	0	0.92	0.94	1E+300	AvP	4.3	4.13	4.3	5.28
MP	0.01	-1E+300	3.59	1E+300	AMEn	12.55	12.46	12.55	13.68
VP	0.01	-1E+300	1.67	1E+300	Arg	10.85	-1E+300	8.5	10.85
					His	3.75	-1E+300	0	3.75
					Iso	6.1	6.07	6.1	6.47
					Leu	11.25	-1E+300	0	11.25
					Lys	8.2	7.32	8.2	8.24
					Met	3.9	2.55	3.9	4.82
					Phe	6.97	-1E+300	0	6.97
					Thr	5.5	5.19	5.5	10.44
					Val	6.98	-1E+300	6.4	6.98
					Ala	7.59	-1E+300	0	7.59

					Asp	9.48	-1E+300	0	9.48
					Cys	1.75	-1E+300	0	1.75
					Glu	14.79	-1E+300	0	14.79
					Gly	7.61	-1E+300	0	7.61
					Pro	7.51	-1E+300	0	7.51
					Ser	7.52	-1E+300	0	7.52
					Tyr	4.88	-1E+300	0	4.88
					Maize	16.83	16.83	70	1E+300
					Wheat	0	0	25	1E+300
					RB	0	0	20	1E+300
					CRM	38.07	38.07	40	1E+300
					SBM	20.25	20.25	30	1E+300
					MBM	0	0	8	1E+300
					FM	6.52	6.52	10	1E+300
					CM	10.04	10.04	20	1E+300
					BSFL	0	0	23.93	1E+300
					CLM	0	0	20	1E+300
					PO	5	0.32	5	5.46
					LiSt	0.94	0.94	10	1E+300
					CaHPO ₄	0	0	1.3	1E+300
					Ca ₃ (PO ₄) ₂	0	0	1.3	1E+300
					L-Lys	0	0	0.56	1E+300
					DL-Met	0.14	0.14	0.23	1E+300
					L-Thre	0.03	0.03	0.53	1E+300
					NaCl	0.17	0.17	0.4	1E+300
					Na ₂ CO ₃	0	0	0.4	1E+300
					MP	1	0.53	1	9.8
					VP	1	0.53	1	9.8

Objective Cost: 1.03/kg

Appendix 19: Layer developer at the upper limit energy requirement

Variable	Amount	Valid Cost Range			Constraint	Amount	Valid RHS Range		
		Lower Bound	Current	Upper Range			Lower Bound	Current	Upper Range
Maize	0.4642	0.83	0.86	1.1	Weight	1	0.98	1	1.04
Wheat	0	0.91	11.73	1E+300	DM	891.01	-1E+300	0	891.01
RB	0	0.44	0.79	1E+300	Ash	36.11	-1E+300	0	36.11
CRM	0.127	0.39	0.63	0.67	GE	16.9	-1E+300	0	16.9
SBM	0.1235	1.14	1.59	2.11	CP	155	147.91	155	159.32
MBM	0	0.72	1.78	1E+300	Fat	75.69	-1E+300	0	75.69
FM	0.0406	-1.75	1.78	2.37	Starch	394.77	-1E+300	0	394.77
CM	0.1583	0.10	0.52	0.79	NDF	148.83	-1E+300	0	148.83
BSFL	0	2.31	8.29	1E+300	ADF	63.63	-1E+300	0	63.63
CLM	0	0.76	7.35	1E+300	Ca	8	2.92	8	9
PO	0.05	-2E+15	1.67	2.89	Ca	8	8	9	1E+300
LiSt	0.0139	-0.70	0.06	5.71	Mg	1.74	-1E+300	0	1.74
CaHPO ₄	0	-3.61	2.52	1E+300	Mg	1.74	-1E+300	0	1.74
Ca ₃ (PO ₄) ₂	0	-4.06	7.35	1E+300	K	9.19	-1E+300	0	9.19
L-Lys	0	-11.31	6.09	1E+300	K	9.19	-1E+300	0	9.19
DL-Met	0.0005	3.79	11.79	64.38	Na	1.5	0.65	1.5	1.8
L-Thre	0	3.65	8.39	1E+300	Na	1.5	1.5	1.8	1E+300
NaCl	0	0.78	0.8	1E+300	AvP	3.9	-1E+300	3.8	3.90
Na ₂ CO ₃	0.002	-0.73	0.94	0.97	AvP	3.9	3.8	3.9	5.14
MP	0.01	-1E+300	3.59	1E+300	AMEn	12.55	11.99	12.55	12.85

VP	0.01	-1E+300	1.67	1E+300	Arg	9.56	-1E+300	6.3	9.56
					His	3.27	-1E+300	0	3.27
					Iso	5.1	-1E+300	4.5	5.1
					Leu	10.89	-1E+300	0	10.89
					Lys	6	5.69	6	6.67
					Met	2.8	2.32	2.8	4.17
					Phe	6.16	-1E+300	0	6.16
					Thr	4.37	-1E+300	4.1	4.37
					Val	6.23	-1E+300	4.8	6.23
					Ala	7.13	-1E+300	0	7.13
					Asp	7.93	-1E+300	0	7.93
					Cys	1.74	-1E+300	0	1.74
					Glu	13.06	-1E+300	0	13.06
					Gly	6.6	-1E+300	0	6.60
					Pro	7.25	-1E+300	0	7.25
					Ser	6.45	-1E+300	0	6.45
					Tyr	4.09	-1E+300	0	4.09
					Maize	46.42	46.42	70	1E+300
					Wheat	0	0	25	1E+300
					RB	0	0	20	1E+300
					CRM	12.7	12.7	40	1E+300
					SBM	12.35	12.35	30	1E+300
					MBM	0	0	8	1E+300
					FM	4.06	4.06	10	1E+300
					CM	15.83	15.83	20	1E+300
					BSFL	0	0	23.93	1E+300
					CLM	0	0	20	1E+300
					PO	5	3.51	5	7.27
					LiSt	1.39	1.39	10	1E+300
					CaHPO ₄	0	0	1.3	1E+300
					Ca ₃ (PO ₄) ₂	0	0	1.3	1E+300
					L-Lys	0	0	0.42	1E+300
					DL-Met	0.05	0.05	0.19	1E+300
					L-Thre	0	0	0.35	1E+300
					NaCl	0	0	0.4	1E+300
					Na ₂ CO ₃	0.2	0.2	0.4	1E+300
					MP	1	0	1	2.8
					VP	1	0	1	2.8

Objective Cost: 0.97/kg

Appendix 20: Layer pre-lay at the upper limit energy requirement

Variable	Amount	Valid Cost Range			Constraint	Amount	Valid RHS Range		
		Lower Bound	Current	Upper Range			Lower Bound	Current	Upper Range
Maize	0.4097	0.79	0.86	0.88	Weight	1	0.99	1	1.06
Wheat	0	0.89	11.73	1E+300	DM	894.07	-1E+300	0	894.07
RB	0	0.68	0.79	1E+300	Ash	38.7	-1E+300	0	38.7
CRM	0.1663	0.61	0.63	0.7	GE	16.6	-1E+300	0	16.6
SBM	0.1476	1.55	1.59	2.33	CP	165.67	-1E+300	165	165.67
MBM	0	0.91	1.78	1E+300	Fat	76.3	-1E+300	0	76.3
FM	0.0643	-3.18	1.78	1.85	Starch	388.42	-1E+300	0	388.42
CM	0.1024	0.35	0.52	0.58	NDF	119.38	-1E+300	0	119.38
BSFL	0	2.1	8.29	1E+300	ADF	52.11	-1E+300	0	52.11
CLM	0	0.56	7.35	1E+300	Ca	18	4.07	18	20.54

PO	0.05	-1E+300	1.67	2.23	Ca	18	18	25	1E+300
LiSt	0.037	-0.29	0.06	10.2	Mg	2.16	-1E+300	0	2.16
CaHPO ₄	0	-0.31	2.52	1E+300	Mg	2.16	-1E+300	0	2.16
Ca ₃ (PO ₄) ₂	0	-0.18	7.35	1E+300	K	8.69	-1E+300	0	8.69
L-Lys	0	-18.16	6.09	1E+300	K	8.69	-1E+300	0	8.69
DL-Met	0.001	4.76	11.79	142.54	Na	1.5	0.85	1.5	1.8
L-Thre	0.0001	0.57	8.39	113.59	Na	1.5	1.5	1.8	1E+300
NaCl	0.0017	-0.29	0.8	0.82	AvP	4.3	-1E+300	4.2	4.3
Na ₂ CO ₃	0	0.92	0.94	1E+300	AvP	4.3	4.2	4.3	5.3
MP	0.01	-1E+300	3.59	1E+300	AMEn	12.55	11.52	12.55	12.65
VP	0.01	-1E+300	1.67	1E+300	Arg	9.82	-1E+300	7.5	9.82
					His	3.55	-1E+300	0	3.55
					Iso	5.6	5.57	5.6	5.77
					Leu	11.44	-1E+300	0	11.44
					Lys	7.2	6.82	7.2	7.74
					Met	3.5	2.55	3.5	4.43
					Phe	6.52	-1E+300	0	6.52
					Thr	5	4.86	5	8.32
					Val	6.62	-1E+300	6.1	6.62
					Ala	7.81	-1E+300	0	7.81
					Asp	8.54	-1E+300	0	8.54
					Cys	1.78	-1E+300	0	1.78
					Glu	13.42	-1E+300	0	13.42
					Gly	7.54	-1E+300	0	7.54
					Pro	7.78	-1E+300	0	7.78
					Ser	7.08	-1E+300	0	7.08
					Tyr	4.56	-1E+300	0	4.56
					Maize	40.97	40.97	70	1E+300
					Wheat	0	0	25	1E+300
					RB	0	0	20	1E+300
					CRM	16.63	16.63	40	1E+300
					SBM	14.76	14.76	30	1E+300
					MBM	0	0	8	1E+300
					FM	6.43	6.43	10	1E+300
					CM	10.24	10.24	20	1E+300
					BSFL	0	0	23.93	1E+300
					CLM	0	0	20	1E+300
					PO	5	4.55	5	9.54
					LiSt	3.7	3.70	10	1E+300
					CaHPO ₄	0	0	1.3	1E+300
					Ca ₃ (PO ₄) ₂	0	0	1.3	1E+300
					L-Lys	0	0	0.42	1E+300
					DL-Met	0.1	0.1	0.19	1E+300
					L-Thre	0.01	0.01	0.35	1E+300
					NaCl	0.17	0.17	0.4	1E+300
					Na ₂ CO ₃	0	0	0.4	1E+300
					MP	1	0	1	1.67
					VP	1	0	1	1.67

Objective Cost: 1.01/kg

Appendix 21: Layer peaking at the upper limit energy requirement

Variable	Amount	Valid Cost Range			Constraint	Amount	Valid RHS Range		
		Lower Bound	Current	Upper Range			Lower Bound	Current	Upper Range
Maize	0.5924	-3.84	0.86	3.51	Weight	1	1	1	1.01
Wheat	0	-0.75	11.73	1E+300	DM	903.65	-1E+300	0	903.65
RB	0	-5.09	0.79	1E+300	Ash	46.73	-1E+300	0	46.73
CRM	0	-2.55	0.63	1E+300	GE	17.13	-1E+300	0	17.13
SBM	0.0068	-36.38	1.59	4.87	CP	192.97	-1E+300	178	192.97
MBM	0.0227	-7.07	1.78	27.5	Fat	101.46	-1E+300	0	101.46
FM	0.0356	-55.56	1.78	5.12	Starch	384.66	-1E+300	0	384.66
CM	0	-8.61	0.52	1E+300	NDF	110.56	-1E+300	0	110.56
BSFL	0.2148	6.77	8.29	1E+300	ADF	44.34	-1E+300	0	44.34
CLM	0	-15.21	7.35	1E+300	Ca	33.3	29.94	33.3	34.43
PO	0.05	-1E+300	1.67	63.48	Ca	33.3	33.3	44.4	1E+300
LiSt	0.0542	-87.62	0.06	17.07	Mg	2.58	-1E+300	0	2.58
CaHPO ₄	0	-40.13	2.52	1E+300	Mg	2.58	-1E+300	0	2.58
Ca ₃ (PO ₄) ₂	0	-33.42	7.35	1E+300	K	4.46	-1E+300	0	4.46
L-Lys	0	-504.29	6.09	1E+300	K	4.46	-1E+300	0	4.46
DL-Met	0.0021	-4E+17	11.79	14.87	Na	1.6	0.99	1.6	2
L-Thre	0	-4.02	8.39	1E+300	Na	1.6	1.6	2	1E+300
NaCl	0	-2.80	0.8	1E+300	AvP	4.8	-1E+300	3.6	4.8
Na ₂ CO ₃	0.0014	-38.01	0.94	4.95	AvP	4.8	4.18	4.8	5.63
MP	0.01	-1E+300	3.59	1E+300	AMEn	13.8	13.68	13.8	13.84
VP	0.01	-1E+300	1.67	1E+300	Arg	8.6	8.36	8.6	8.78
					His	3.83	-1E+300	0	3.83
					Iso	6.82	-1E+300	6.6	6.82
					Leu	13.73	-1E+300	0	13.73
					Lys	8.3	8.03	8.3	8.73
					Met	5.36	-1E+300	4.2	5.36
					Phe	6.87	-1E+300	0	6.87
					Thr	6.05	-1E+300	5.8	6.05
					Val	9.19	-1E+300	7.3	9.19
					Ala	11.64	-1E+300	0	11.64
					Asp	11.57	-1E+300	0	11.57
					Cys	1.52	-1E+300	0	1.52
					Glu	15.06	-1E+300	0	15.06
					Gly	10.65	-1E+300	0	10.65
					Pro	11.29	-1E+300	0	11.29
					Ser	7.65	-1E+300	0	7.65
					Tyr	8.3	-1E+300	0	8.3
					Maize	59.24	59.24	70	1E+300
					Wheat	0	0	25	1E+300
					RB	0	0	25	1E+300
					CRM	0	0	40	1E+300
					SBM	0.68	0.68	30	1E+300
					MBM	2.27	2.27	8	1E+300
					FM	3.56	3.56	10	1E+300
					CM	0	0	20	1E+300
					BSFL	21.48	21.48	23.93	1E+300
					CLM	0	0	20	1E+300
					PO	5	4.82	5	5.52
					LiSt	5.42	5.42	10	1E+300
					CaHPO ₄	0	0	1.3	1E+300

					Ca ₃ (PO ₄) ₂	0	0	1.3	1E+300
					L-Lys	0	0	0.49	1E+300
					DL-Met	0.21	0.09	0.21	2.36
					L-Thre	0	0	0.44	1E+300
					NaCl	0	0	0.4	1E+300
					Na ₂ CO ₃	0.14	0.14	0.4	1E+300
					MP	1	0.12	1	1.30
					VP	1	0.12	1	1.30
Objective Cost: 2.57/kg									

Appendix 22: Layer phase 2 at the upper limit energy requirement

Variable	Amount	Valid Cost Range			Constraint	Amount	Valid RHS Range		
		Lower Bound	Current	Upper Range			Lower Bound	Current	Upper Range
Maize	0.6332	-3.84	0.86	3.51	Weight	1	0.99	1	1
Wheat	0	-0.75	11.73	1E+300	DM	902.45	-1E+300	0	902.45
RB	0	-5.09	0.79	1E+300	Ash	37.2	-1E+300	0	37.2
CRM	0	-2.55	0.63	1E+300	GE	16.72	-1E+300	0	16.72
SBM	0.0253	-36.38	1.59	4.87	CP	168.85	-1E+300	160	168.85
MBM	0.0037	-7.07	1.78	27.5	Fat	95	-1E+300	0	95
FM	0.0532	-55.56	1.78	5.12	Starch	410.57	-1E+300	0	410.57
CM	0	-8.61	0.52	1E+300	NDF	100.92	-1E+300	0	100.92
BSFL	0.1414	6.77	8.29	1E+300	ADF	37.91	-1E+300	0	37.91
CLM	0	-15.21	7.35	1E+300	Ca	35	33.99	35	39.21
PO	0.05	-1E+300	1.67	63.48	Ca	35	35	42	1E+300
LiSt	0.0691	-87.62	0.06	17.07	Mg	2.72	-1E+300	0	2.72
CaHPO ₄	0	-40.13	2.52	1E+300	Mg	2.72	-1E+300	0	2.72
Ca ₃ (PO ₄) ₂	0	-33.42	7.35	1E+300	K	4.35	-1E+300	0	4.35
L-Lys	0	-504.29	6.09	1E+300	K	4.35	-1E+300	0	4.35
DL-Met	0.003	-4E+17	11.79	14.87	Na	1.4	0.94	1.4	1.7
L-Thre	0	-4.02	8.39	1E+300	Na	1.4	1.4	1.7	1E+300
NaCl	0	-2.80	0.8	1E+300	AvP	4.1	-1E+300	3.4	4.1
Na ₂ CO ₃	0.0011	-38.01	0.94	4.95	AvP	4.1	3.73	4.1	4.35
MP	0.01	-1E+300	3.59	1E+300	AMEn	13.6	13.56	13.6	13.75
VP	0.01	-1E+300	1.67	1E+300	Arg	7.7	7.63	7.7	8.14
					His	3.53	-1E+300	0	3.53
					Iso	5.97	-1E+300	5.9	5.97
					Leu	12.57	-1E+300	0	12.57
					Lys	7.4	6.92	7.4	7.47
					Met	5.96	-1E+300	3.7	5.96
					Phe	6.22	-1E+300	0	6.22
					Thr	5.35	-1E+300	5.2	5.35
					Val	7.81	-1E+300	6.5	7.81
					Ala	10.06	-1E+300	0	10.06
					Asp	9.69	-1E+300	0	9.69
					Cys	1.55	-1E+300	0	1.55
					Glu	12.85	-1E+300	0	12.85
					Gly	8.94	-1E+300	0	8.94
					Pro	9.76	-1E+300	0	9.76
					Ser	6.97	-1E+300	0	6.97
					Tyr	6.76	-1E+300	0	6.76
					Maize	63.32	63.32	70	1E+300
					Wheat	0	0	25	1E+300
					RB	0	0	25	1E+300

					CRM	0	0	40	1E+300
					SBM	2.53	2.53	30	1E+300
					MBM	0.37	0.37	8	1E+300
					FM	5.32	5.32	10	1E+300
					CM	0	0	20	1E+300
					BSFL	14.14	14.14	23.93	1E+300
					CLM	0	0	20	1E+300
					PO	5	4.34	5	5.16
					LiSt	6.91	6.91	10	1E+300
					CaHPO ₄	0	0	1.3	1E+300
					Ca ₃ (PO ₄) ₂	0	0	1.3	1E+300
					L-Lys	0	0	0.69	1E+300
					DL-Met	0.3	0.07	0.3	0.95
					L-Thre	0	0	0.47	1E+300
					NaCl	0	0	0.4	1E+300
					Na ₂ CO ₃	0.11	0.11	0.4	1E+300
					MP	1	0.73	1	2.11
					VP	1	0.73	1	2.11

Objective Cost: 2.03/kg

Appendix 23: Layer phase 3 at the upper limit energy requirement

Variable	Amount	Valid Cost Range			Constraint	Amount	Valid RHS Range		
		Lower Bound	Current	Upper Range			Lower Bound	Current	Upper Range
Maize	0.6409	-11.86	0.86	1.91	Weight	1	1	1	1.02
Wheat	0	0.09	11.73	1E+300	DM	901.86	-1E+300	0	901.86
RB	0	-4.66	0.79	1E+300	Ash	33.17	-1E+300	0	33.17
CRM	0	-0.50	0.63	1E+300	GE	16.47	-1E+300	0	16.47
SBM	0.0468	-2.98	1.59	7.22	CP	159	-1E+300	151.8	159
MBM	0	-9.95	1.78	1E+300	Fat	91.85	-1E+300	0	91.85
FM	0.0459	-30.46	1.78	7.38	Starch	415.49	-1E+300	0	415.49
CM	0	-8.78	0.52	1E+300	NDF	98.74	-1E+300	0	98.74
BSFL	0.1162	2.29	8.29	13.77	ADF	36.59	-1E+300	0	36.59
CLM	0	-5.06	7.35	1E+300	Ca	36.7	30.92	36.7	38.3
PO	0.05	-1E+300	1.67	27.03	Ca	36.7	36.7	44	1E+300
LiSt	0.078	-20.59	0.06	42.85	Mg	2.86	-1E+300	0	2.86
CaHPO ₄	0	-35.42	2.52	1E+300	Mg	2.86	-1E+300	0	2.86
Ca ₃ (PO ₄) ₂	0	-37.17	7.35	1E+300	K	4.51	-1E+300	0	4.51
L-Lys	0.0001	-422.58	6.09	271.73	K	4.51	-1E+300	0	4.51
DL-Met	0.0007	6.82	11.79	1268.67	Na	1.4	0.8	1.4	1.7
L-Thre	0	-1.05	8.39	1E+300	Na	1.4	1.4	1.7	1E+300
NaCl	0	-0.61	0.8	1E+300	AvP	3.7	-1E+300	3.1	3.7
Na ₂ CO ₃	0.0014	-15.75	0.94	2.51	AvP	3.7	3.34	3.7	3.85
MP	0.01	-1E+300	3.59	1E+300	AMEn	13.4	13.25	13.4	13.46
VP	0.01	-1E+300	1.67	1E+300	Arg	7.51	-1E+300	7.4	7.51
					His	3.45	-1E+300	0	3.45
					Iso	5.7	5.6	5.7	5.77
					Leu	12.18	-1E+300	0	12.18
					Lys	7.1	7.02	7.1	12.54
					Met	3.5	2.80	3.5	5.77
					Phe	6.08	-1E+300	0	6.08
					Thr	5.09	-1E+300	5	5.09
					Val	7.34	-1E+300	6.2	7.34
					Ala	9.37	-1E+300	0	9.37

					Asp	9.17	-1E+300	0	9.17
					Cys	1.6	-1E+300	0	1.6
					Glu	12.27	-1E+300	0	12.27
					Gly	8.17	-1E+300	0	8.17
					Pro	9.29	-1E+300	0	9.29
					Ser	6.77	-1E+300	0	6.77
					Tyr	6.25	-1E+300	0	6.25
					Maize	64.09	64.09	70	1E+300
					Wheat	0	0	25	1E+300
					RB	0	0	25	1E+300
					CRM	0	0	40	1E+300
					SBM	4.68	4.68	30	1E+300
					MBM	0	0	8	1E+300
					FM	4.59	4.59	10	1E+300
					CM	0	0	20	1E+300
					BSFL	11.62	11.62	23.93	1E+300
					CLM	0	0	20	1E+300
					PO	5	4.75	5	5.56
					LiSt	7.8	7.80	10	1E+300
					CaHPO ₄	0	0	1.3	1E+300
					Ca ₃ (PO ₄) ₂	0	0	1.3	1E+300
					L-Lys	0.01	0.01	0.69	1E+300
					DL-Met	0.07	0.07	0.3	1E+300
					L-Thre	0	0	0.47	1E+300
					NaCl	0	0	0.4	1E+300
					Na ₂ CO ₃	0.14	0.14	0.4	1E+300
					MP	1	0	1	1.42
					VP	1	0	1	1.42

Objective Cost: 1.82/kg

Appendix 24: Layer phase 4 at the upper limit energy requirement

Variable	Amount	Valid Cost Range			Constraint	Amount	Valid RHS Range		
		Lower Bound	Current	Upper Range			Lower Bound	Current	Upper Range
Maize	0.6461	-11.86	0.86	1.91	Weight	1	0.99	1	1.03
Wheat	0	0.09	11.73	1E+300	DM	901.36	-1E+300	0	901.36
RB	0	-4.66	0.79	1E+300	Ash	29.98	-1E+300	0	29.98
CRM	0	-0.50	0.63	1E+300	GE	16.24	-1E+300	0	16.24
SBM	0.0705	-2.98	1.59	7.22	CP	150.71	-1E+300	148.2	150.71
MBM	0	-9.95	1.78	1E+300	Fat	88.5	-1E+300	0	88.5
FM	0.0406	-30.46	1.78	7.38	Starch	418.81	-1E+300	0	418.81
CM	0	-8.78	0.52	1E+300	NDF	95.06	-1E+300	0	95.06
BSFL	0.0842	2.29	8.29	13.77	ADF	34.51	-1E+300	0	34.51
CLM	0	-5.06	7.35	1E+300	Ca	38.3	26.66	38.3	43.63
PO	0.05	-1E+17	1.67	27.03	Ca	38.3	38.3	46	1E+300
LiSt	0.086	-20.59	0.06	42.85	Mg	2.98	-1E+300	0	2.98
CaHPO ₄	0	-35.42	2.52	1E+300	Mg	2.98	-1E+300	0	2.98
Ca ₃ (PO ₄) ₂	0	-37.17	7.35	1E+300	K	4.67	-1E+300	0	4.67
L-Lys	0.0002	-422.58	6.09	271.73	K	4.67	-1E+300	0	4.67
DL-Met	0.0008	6.82	11.79	1268.67	Na	1.4	0.7	1.4	1.7
L-Thre	0	-1.05	8.39	1E+300	Na	1.4	1.4	1.7	1E+300
NaCl	0	-0.61	0.8	1E+300	AvP	3.5	-1E+300	2.9	3.5
Na ₂ CO ₃	0.0016	-15.75	0.94	2.51	AvP	3.5	2.9	3.5	3.8
MP	0.01	-1E+300	3.59	1E+300	AMEn	13.2	12.89	13.2	13.39

VP	0.01	-1E+300	1.67	1E+300	Arg	7.38	-1E+300	7	7.38
					His	3.36	-1E+300	0	3.36
					Iso	5.4	5.29	5.4	5.53
					Leu	11.75	-1E+300	0	11.75
					Lys	6.8	6.64	6.8	12.16
					Met	3.4	2.6	3.4	5.57
					Phe	5.93	-1E+300	0	5.93
					Thr	4.81	-1E+300	4.7	4.81
					Val	6.8	-1E+300	6	6.8
					Ala	8.71	-1E+300	0	8.71
					Asp	8.54	-1E+300	0	8.54
					Cys	1.65	-1E+300	0	1.65
					Glu	11.63	-1E+300	0	11.63
					Gly	7.57	-1E+300	0	7.57
					Pro	8.84	-1E+300	0	8.84
					Ser	6.58	-1E+300	0	6.58
					Tyr	5.63	-1E+300	0	5.63
					Maize	64.61	64.61	70	1E+300
					Wheat	0	0	25	1E+300
					RB	0	0	25	1E+300
					CRM	0	0	40	1E+300
					SBM	7.05	7.052	30	1E+300
					MBM	0	0	8	1E+300
					FM	4.06	4.06	10	1E+300
					CM	0	0	20	1E+300
					BSFL	8.42	8.42	23.93	1E+300
					CLM	0	0	20	1E+300
					PO	5	4.17	5	6.14
					LiSt	8.6	8.6	10	1E+300
					CaHPO ₄	0	0	1.3	1E+300
					Ca ₃ (PO ₄) ₂	0	0	1.3	1E+300
					L-Lys	0.02	0.02	0.69	1E+300
					DL-Met	0.08	0.081	0.3	1E+300
					L-Thre	0	0	0.47	1E+300
					NaCl	0	0	0.4	1E+300
					Na ₂ CO ₃	0.16	0.16	0.4	1E+300
					MP	1	0	1	2.4
					VP	1	0	1	2.4

Objective Cost: 1.59/kg

Appendix 25: Layer phase 5 at the upper limit energy requirement

Variable	Amount	Valid Cost Range			Constraint	Amount	Valid RHS Range		
		Lower Bound	Current	Upper Range			Lower Bound	Current	Upper Range
Maize	0.66	-11.86	0.86	1.91	Weight	1	0.99	1	1.02
Wheat	0	0.09	11.73	1E+300	DM	901.53	-1E+300	0	901.53
RB	0	-4.66	0.79	1E+300	Ash	27.82	-1E+300	0	27.82
CRM	0	-0.50	0.63	1E+300	GE	16.16	-1E+300	0	16.16
SBM	0.0607	-2.98	1.59	7.22	CP	142.34	-1E+300	140.9	142.34
MBM	0	-9.95	1.78	1E+300	Fat	88.03	-1E+300	0	88.03
FM	0.0303	-30.46	1.78	7.38	Starch	427.71	-1E+300	0	427.71
CM	0	-8.78	0.52	1E+300	NDF	95.89	-1E+300	0	95.89
BSFL	0.0865	2.29	8.29	13.77	ADF	34.52	-1E+300	0	34.52
CLM	0	-5.06	7.35	1E+300	Ca	39.2	30.8	39.2	42.94

PO	0.05	-2E+17	1.67	27.03	Ca	39.2	39.2	47	1E+300
LiSt	0.0896	-20.59	0.06	42.85	Mg	3.02	-1E+300	0	3.02
CaHPO ₄	0	-35.42	2.52	1E+300	Mg	3.02	-1E+300	0	3.02
Ca ₃ (PO ₄) ₂	0	-37.17	7.35	1E+300	K	4.46	-1E+300	0	4.46
L-Lys	0.0004	-422.58	6.09	271.73	K	4.46	-1E+300	0	4.46
DL-Met	0.0008	6.82	11.79	1268.67	Na	1.4	0.61	1.4	1.7
L-Thre	0	-1.05	8.39	1E+300	Na	1.4	1.4	1.7	1E+300
NaCl	0	-0.61	0.8	1E+300	AvP	3.2	-1E+300	2.7	3.2
Na ₂ CO ₃	0.0018	-15.75	0.94	2.51	AvP	3.2	2.88	3.2	3.74
MP	0.01	-1E+300	3.59	1E+300	AMEn	13.2	12.92	13.2	13.33
VP	0.01	-1E+300	1.67	1E+300	Arg	6.87	-1E+300	6.6	6.87
					His	3.19	-1E+300	0	3.19
					Iso	5.1	5.05	5.1	5.34
					Leu	11.29	-1E+300	0	11.29
					Lys	6.4	6.12	6.4	11.64
					Met	3.2	2.46	3.2	5.42
					Phe	5.62	-1E+300	0	5.62
					Thr	4.54	-1E+300	4.5	4.54
					Val	6.49	-1E+300	5.6	6.49
					Ala	8.32	-1E+300	0	8.32
					Asp	8.12	-1E+300	0	8.12
					Cys	1.59	-1E+300	0	1.59
					Glu	11	-1E+300	0	11
					Gly	7.07	-1E+300	0	7.07
					Pro	8.54	-1E+300	0	8.54
					Ser	6.2	-1E+300	0	6.2
					Tyr	5.41	-1E+300	0	5.41
					Maize	66	66	70	1E+300
					Wheat	0	0	25	1E+300
					RB	0	0	25	1E+300
					CRM	0	0	40	1E+300
					SBM	6.07	6.07	30	1E+300
					MBM	0	0	8	1E+300
					FM	3.03	3.03	10	1E+300
					CM	0	0	20	1E+300
					BSFL	8.65	8.65	23.93	1E+300
					CLM	0	0	20	1E+300
					PO	5	4.42	5	6.17
					LiSt	8.96	8.96	10	1E+300
					CaHPO ₄	0	0	1.3	1E+300
					Ca ₃ (PO ₄) ₂	0	0	1.3	1E+300
					L-Lys	0.04	0.04	0.69	1E+300
					DL-Met	0.08	0.08	0.3	1E+300
					L-Thre	0	0	0.47	1E+300
					NaCl	0	0	0.4	1E+300
					Na ₂ CO ₃	0.18	0.18	0.4	1E+300
					MP	1	0	1	1.98
					VP	1	0	1	1.98

Objective Cost: 1.59/kg

Appendix 26: Sensitivity result for broiler diet with zero maize inclusion

Variable	Amount	Valid Cost Range			Constraint	Amount	Valid RHS Range		
		Lower Bound	Current	Upper Range			Lower Bound	Current	Upper Range
Maize					Weight		64		
Wheat					DM		4		
RB					Ash		21		
CRM					GE		16		
SBM					CP		57		
MBM					Fat		22		
FM					Starch		26		
CM					NDF		43		
BSFL					ADF		27		
CLM					Ca		72		
PO					Ca		31		
LiSt					Mg		11		
CaHPO ₄					Mg		32		
Ca ₃ (PO ₄) ₂					K		28		
L-Lys					K		46		
DL-Met					Na		54		
L-Thre					Na		71		
NaCl					AvP		29		
Na ₂ CO ₃					AvP		37		
MP					AMEn		33		
VP					Arg		-1		
					His		44		
					Iso		42		
					Leu		24		
					Lys		8		
					Met		6		
					Phe		25		
					Thr		23		
					Val		3		
					Ala		40		
					Asp		47		
					Cys		48		
					Glu		49		
					Gly		50		
					Pro		51		
					Ser		52		
					Tyr		53		
					Maize		0		
					Wheat		60		
					RB		56		
					CRM		17		
					SBM		58		
					MBM		59		
					FM		66		
					CM		61		
					BSFL		1		
					CLM		63		
					PO		10		
					LiSt		65		
					CaHPO ₄		68		

					Ca ₃ (PO ₄) ₂		67		
					L-Lys		14		
					DL-Met		15		
					L-Thre		45		
					NaCl		35		
					Na ₂ CO ₃		41		
					MP		19		
					VP		20		
Objective Cost: No Solution									

Appendix 27: Sensitivity result for broiler diet with zero soybean meal inclusion

Variable	Amount	Valid Cost Range			Constraint	Amount	Valid RHS Range		
		Lower Bound	Current	Upper Range			Lower Bound	Current	Upper Range
Maize					Weight		63		
Wheat					DM		4		
RB					Ash		21		
CRM					GE		16		
SBM					CP		7		
MBM					Fat		22		
FM					Starch		26		
CM					NDF		69		
BSFL					ADF		27		
CLM					Ca		72		
PO					Ca		31		
LiSt					Mg		8		
CaHPO ₄					Mg		32		
Ca ₃ (PO ₄) ₂					K		46		
L-Lys					K		34		
DL-Met					Na		54		
L-Thre					Na		36		
NaCl					AvP		29		
Na ₂ CO ₃					AvP		37		
MP					AMEn		60		
VP					Arg		-1		
					His		44		
					Iso		-1		
					Leu		30		
					Lys		43		
					Met		24		
					Phe		25		
					Thr		23		
					Val		0		
					Ala		40		
					Asp		47		
					Cys		48		
					Glu		49		
					Gly		50		
					Pro		51		
					Ser		52		
					Tyr		53		
					Maize		55		
					Wheat		9		
					RB		57		

					CRM		58		
					SBM		28		
					MBM		59		
					FM		66		
					CM		6		
					BSFL		1		
					CLM		33		
					PO		10		
					LiSt		65		
					CaHPO ₄		68		
					Ca ₃ (PO ₄) ₂		67		
					L-Lys		14		
					DL-Met		15		
					L-Thre		70		
					NaCl		71		
					Na ₂ CO ₃		18		
					MP		19		
					VP		20		
Objective Cost: No Solution									

Appendix 28: Sensitivity result for broiler diet with zero maize and soybean meal inclusion

Variable	Amount	Valid Cost Range			Constraint	Amount	Valid RHS Range		
		Lower Bound	Current	Upper Range			Lower Bound	Current	Upper Range
Maize					Weight	30			
Wheat					DM	4			
RB					Ash	21			
CRM					GE	16			
SBM					CP	7			
MBM					Fat	22			
FM					Starch	26			
CM					NDF	43			
BSFL					ADF	27			
CLM					Ca	71			
PO					Ca	31			
LiSt					Mg	8			
CaHPO ₄					Mg	32			
Ca ₃ (PO ₄) ₂					K	3			
L-Lys					K	62			
DL-Met					Na	54			
L-Thre					Na	46			
NaCl					AvP	29			
Na ₂ CO ₃					AvP	37			
MP					AMEn	59			
VP					Arg	-1			
					His	44			
					Iso	-1			
					Leu	-1			
					Lys	33			
					Met	6			
					Phe	25			
					Thr	23			
					Val	36			
					Ala	40			

					Asp		47		
					Cys		48		
					Glu		49		
					Gly		50		
					Pro		51		
					Ser		52		
					Tyr		53		
					Maize		0		
					Wheat		9		
					RB		56		
					CRM		57		
					SBM		28		
					MBM		58		
					FM		65		
					CM		60		
					BSFL		1		
					CLM		24		
					PO		10		
					LiSt		64		
					CaHPO ₄		67		
					Ca ₃ (PO ₄) ₂		66		
					L-Lys		14		
					DL-Met		15		
					L-Thre		45		
					NaCl		70		
					Na ₂ CO ₃		18		
					MP		19		
					VP		20		

Objective Cost: No Solution

Appendix 29: Sensitivity result for layer diet with zero maize inclusion

Variable	Amount	Valid Cost Range			Constraint	Amount	Valid RHS Range		
		Lower Bound	Current	Upper Range			Lower Bound	Current	Upper Range
Maize	0	-1E+300	0.86	1E+300	Weight	1	1	1	1
Wheat	0.0997	7.99	11.73	17.67	DM	903	-1E+300	0	903
RB	0.0986	-6.14	0.79	8.41	Ash	45	-1E+300	0	45
CRM	0.4	-1E+300	0.63	13.65	GE	16	-1E+300	0	16
SBM	0.086	-42.80	1.59	3.95	CP	158	-1E+300	148.2	158
MBM	0	-29.42	1.78	1E+300	Fat	86	-1E+300	0	86
FM	0	-11.29	1.78	1E+300	Starch	383	-1E+300	0	383
CM	0	-2.66	0.52	1E+300	NDF	92	-1E+300	0	92
BSFL	0.1529	5.97	8.29	12.44	ADF	51	-1E+300	0	51
CLM	0	2.97	7.35	1E+300	Ca	38.3	32.6	38.3	46
PO	0.05	-8E+15	1.67	52.47	Ca	38.3	38.3	46	1E+300
LiSt	0.0826	-8.71	0.06	18.42	Mg	3.6	-1E+300	0	3.6
CaHPO ₄	0	-90.37	2.52	1E+300	Mg	3.6	-1E+300	0	3.6
Ca ₃ (PO ₄) ₂	0	-108.57	7.35	1E+300	K	8.2	-1E+300	0	8.2
L-Lys	0	-74.64	6.09	1E+300	K	8.2	-1E+300	0	8.2
DL-Met	0.003	-3E+17	11.79	24.48	Na	1.4	0.3	1.4	1.7
L-Thre	0.0047	-3E+18	8.39	13.60	Na	1.4	1.4	1.7	1E+300
NaCl	0	0.23	0.8	1E+300	AvP	3.5	-1E+300	2.9	3.5
Na ₂ CO ₃	0.0025	-6.62	0.94	1.57	AvP	3.5	2.9	3.5	3.9
MP	0.01	-1E+300	3.59	1E+300	AMEn	12.6	12.48	12.6	12.96

VP	0.01	-1E+300	1.67	1E+300	Arg	7.5	-1E+300	7	7.5
					His	3	-1E+300	0	3
					Iso	5.5	-1E+300	5.4	5.5
					Leu	9.1	-1E+300	0	9.1
					Lys	6.8	6.7	6.8	10.3
					Met	5.2	-1E+300	3.4	5.2
					Phe	5.5	-1E+300	0	5.5
					Thr	9.3	-1E+300	4.7	9.3
					Val	7	-1E+300	6	7
					Ala	7.1	-1E+300	0	7.1
					Asp	9.4	-1E+300	0	9.4
					Cys	1.2	-1E+300	0	1.2
					Glu	13	-1E+300	0	13
					Gly	6.3	-1E+300	0	6.3
					Pro	7.7	-1E+300	0	7.7
					Ser	5.9	-1E+300	0	5.9
					Tyr	6.2	-1E+300	0	6.2
					Maize	0	0	0	4.44
					Wheat	9.97	9.97	25	1E+300
					RB	9.86	9.86	25	1E+300
					CRM	40	27.54	40	42.67
					SBM	8.6	8.60	30	1E+300
					MBM	0	0	8	1E+300
					FM	0	0	10	1E+300
					CM	0	0	20	1E+300
					BSFL	15.29	15.29	23.93	1E+300
					CLM	0	0	20	1E+300
					PO	5	3.42	5	5.43
					LiSt	8.26	8.26	10	1E+300
					CaHPO ₄	0	0	1.3	1E+300
					Ca ₃ (PO ₄) ₂	0	0	1.3	1E+300
					L-Lys	0	0	0.69	1E+300
					DL-Met	0.3	0.12	0.3	1.39
					L-Thre	0.47	0.01	0.47	3.24
					NaCl	0	0	0.4	1E+300
					Na ₂ CO ₃	0.25	0.25	0.4	1E+300
					MP	1	0	1	3.46
					VP	1	0	1	3.46

Objective Cost: 3.12/kg

Appendix 30: Sensitivity result for layer diet with zero soybean meal inclusion

Variable	Amount	Valid Cost Range			Constraint	Amount	Valid RHS Range		
		Lower Bound	Current	Upper Range			Lower Bound	Current	Upper Range
Maize	0.5616	0.79	0.86	1.30	Weight	1	1	1	1
Wheat	0	1.25	11.73	1E+300	DM	903	-1E+300	0	903
RB	0	-2.75	0.79	1E+300	Ash	37	-1E+300	0	37
CRM	0	0.17	0.63	1E+300	GE	16	-1E+300	0	16
SBM	0	-1E+300	1.59	1E+300	CP	159	-1E+300	148.2	159
MBM	0	-10.02	1.78	1E+300	Fat	90	-1E+300	0	90
FM	0.0254	1.05	1.78	7.41	Starch	364	-1E+300	0	364
CM	0.1127	-16.34	0.52	0.61	NDF	148	-1E+300	0	148
BSFL	0.1449	6.35	8.29	52.83	ADF	61	-1E+300	0	61
CLM	0	1.14	7.35	1E+300	Ca	38.3	35.7	38.3	45.5

PO	0.05	-2E+15	1.67	1.92	Ca	38.3	38.3	46	1E+300
LiSt	0.082	-0.72	0.06	1.65	Mg	3.1	-1E+300	0	3.1
CaHPO ₄	0	-33.26	2.52	1E+300	Mg	3.1	-1E+300	0	3.1
Ca ₃ (PO ₄) ₂	0	-40.61	7.35	1E+300	K	6.2	-1E+300	0	6.2
L-Lys	0.001	-435.90	6.09	24.46	K	6.2	-1E+300	0	6.2
DL-Met	0.0008	0.69	11.79	107.83	Na	1.4	0.7	1.4	1.7
L-Thre	0	0.20	8.39	1E+300	Na	1.4	1.4	1.7	1E+300
NaCl	0	0.78	0.8	1E+300	AvP	3.5	-1E+300	2.9	3.5
Na ₂ CO ₃	0.0016	-0.70	0.94	0.96	AvP	3.5	3.4	3.5	5.1
MP	0.01	-1E+300	3.59	1E+300	AMEn	12.6	12.51	12.6	13.31
VP	0.01	-1E+300	1.67	1E+300	Arg	8	-1E+300	7	8
					His	3.1	-1E+300	0	3.1
					Iso	5.4	5.4	5.4	6.2
					Leu	11.4	-1E+300	0	11.4
					Lys	6.8	6	6.8	11.5
					Met	3.4	2.7	3.4	5.6
					Phe	5.8	-1E+300	0	5.8
					Thr	4.7	-1E+300	4.7	4.7
					Val	7.4	-1E+300	6	7.4
					Ala	8.8	-1E+300	0	8.8
					Asp	9.2	-1E+300	0	9.2
					Cys	1.4	-1E+300	0	1.4
					Glu	13.1	-1E+300	0	13.1
					Gly	7.5	-1E+300	0	7.5
					Pro	8.5	-1E+300	0	8.5
					Ser	6.1	-1E+300	0	6.1
					Tyr	6.1	-1E+300	0	6.1
					Maize	56.16	56.16	70	1E+300
					Wheat	0	0	25	1E+300
					RB	0	0	25	1E+300
					CRM	0	0	40	1E+300
					SBM	0	0	0	15.77
					MBM	0	0	8	1E+300
					FM	2.54	2.54	10	1E+300
					CM	11.27	11.27	20	1E+300
					BSFL	14.49	14.49	23.93	1E+300
					CLM	0	0	20	1E+300
					PO	5	1.95	5	5.36
					LiSt	8.20	8.20	10	1E+300
					CaHPO ₄	0	0	1.3	1E+300
					Ca ₃ (PO ₄) ₂	0	0	1.3	1E+300
					L-Lys	0.1	0.1	0.69	1E+300
					DL-Met	0.08	0.08	0.3	1E+300
					L-Thre	0	0	0.47	1E+300
					NaCl	0	0	0.4	1E+300
					Na ₂ CO ₃	0.16	0.16	0.4	1E+300
					MP	1	0.32	1	6.19
					VP	1	0.32	1	6.19

Objective Cost: 1.95/kg

Appendix 31: Sensitivity result for layer diet with zero maize and soybean meal inclusion

Variable	Amount	Valid Cost Range			Constraint	Amount	Valid RHS Range		
		Lower Bound	Current	Upper Range			Lower Bound	Current	Upper Range
Maize	0	-1E+300	0.86	1E+300	Weight	1	1	1	1
Wheat	0.0665	10.3	11.73	16.37	DM	906	-1E+300	0	906
RB	0.0768	0.16	0.79	5.77	Ash	51	-1E+300	0	51
CRM	0.4	-1E+300	0.63	13.4	GE	16	-1E+300	0	16
SBM	0	-1E+300	1.59	1E+300	CP	170	-1E+300	148.2	170
MBM	0	-30.68	1.78	1E+300	Fat	91	-1E+300	0	91
FM	0	-9.92	1.78	1E+300	Starch	357	-1E+300	0	357
CM	0.0634	-21.32	0.52	0.76	NDF	125	-1E+300	0	125
BSFL	0.2393	-3E+16	8.29	9.4	ADF	67	-1E+300	0	67
CLM	0	5.34	7.35	1E+300	Ca	38.3	33	38.3	46
PO	0.05	-1E+300	1.67	41.56	Ca	38.3	38.3	46	1E+300
LiSt	0.0742	-0.92	0.06	5.52	Mg	3.5	-1E+300	0	3.51690063
CaHPO ₄	0	-94.11	2.52	1E+300	Mg	3.5	-1E+300	0	3.51690063
Ca ₃ (PO ₄) ₂	0	-115.49	7.35	1E+300	K	8.4	-1E+300	0	8.36625263
L-Lys	0.00003	-34.54	6.09	312.45	K	8.4	-1E+300	0	8.36625263
DL-Met	0.003	-2E+19	11.79	21.42	Na	1.4	0.5	1.4	1.7
L-Thre	0.0047	-2E+17	8.39	13.58	Na	1.4	1.4	1.7	1E+300
NaCl	0	0.76	0.8	1E+300	AvP	3.5	-1E+300	2.9	3.5
Na ₂ CO ₃	0.0021	-0.93	0.94	0.99	AvP	3.5	2.9	3.5	3.7
MP	0.01	-1E+300	3.59	1E+300	AMEn	12.6	11.95	12.6	12.97
VP	0.01	-1E+300	1.67	1E+300	Arg	7.7	-1E+300	7	7.7
					His	2.9	-1E+300	0	2.9
					Iso	5.8	-1E+300	5.4	5.8
					Leu	9.4	-1E+300	0	9.4
					Lys	6.8	6.8	6.8	12.3
					Met	5.4	-1E+300	3.4	5.4
					Phe	5.5	-1E+300	0	5.5
					Thr	9.5	-1E+300	4.7	9.5
					Val	8	-1E+300	6	8
					Ala	8.2	-1E+300	0	8.2
					Asp	10.5	-1E+300	0	10.5
					Cys	1	-1E+300	0	1
					Glu	14.2	-1E+300	0	14.2
					Gly	7	-1E+300	0	7
					Pro	8	-1E+300	0	8
					Ser	5.7	-1E+300	0	5.7
					Tyr	7.4	-1E+300	0	7.4
					Maize	0	0	0	5.87
					Wheat	6.65	6.65	25	1E+300
					RB	7.68	7.68	25	1E+300
					CRM	40	38.84	40	45.76
					SBM	0	0	0	0.11
					MBM	0	0	8	1E+300
					FM	0	0	10	1E+300
					CM	6.34	6.34	20	1E+300
					BSFL	23.93	21.95	23.93	24.04
					CLM	0	0	20	1E+300
					PO	5	4.37	5	6.82
					LiSt	7.42	7.42	10	1E+300
					CaHPO ₄	0	0	1.3	1E+300

					Ca ₃ (PO ₄) ₂	0	0	1.3	1E+300
					L-Lys	0.003	0.003	0.69	1E+300
					DL-Met	0.3	0.09	0.3	3.86
					L-Thre	0.47	0	0.47	6.14
					NaCl	0	0	0.4	1E+300
					Na ₂ CO ₃	0.21	0.21	0.4	1E+300
					MP	1	0	1	3.41
					VP	1	0	1	3.41
Objective Cost: 3.33/kg									