Optimization of the Nutrient Content and Protein Quality of Cereal—Legume Blends for Use as Complementary Foods in Ghana

Article *in* European Journal of Marketing · September 2014

DOI: 10.1177/156482651403500309

Optimization of the nutrient content and protein quality of cereal–legume blends for use as complementary foods in Ghana

Devika J. Suri, Kwaku Tano-Debrah, and Shibani A. Ghosh

Abstract

Background. *Nutritionally adequate complementary foods made from locally available ingredients are of high priority in developing countries, including Ghana. The majority of complementary foods in these countries are cereal-based and are unable to meet the nutrient intakes recommended by the World Health Organization.*

Objective. *To evaluate the nutrient content and protein quality of local cereal–legume blends for complementary foods against recommendations and to determine the quantities of additional ingredients required to meet needs by using linear programming.*

Methods. *Nine cereal–legume combinations (maize, sorghum, or millet combined with cowpea, peanut, or soybean) and* koko *(a traditional Ghanaian maize-based complementary food) were evaluated based on the macronutrient targets for a daily ration of complementary food for the age group 12 to 24 months: 264 kcal, 6.5 g of protein, and 8.2 to 11.7 g of fat. Protein quality was assessed by the Protein Digestibility Corrected Amino Acid Score (PDCAAS). Linear programming was then used to determine the amounts of additional oil, sugar, and lysine needed to meet macronutrient requirements.*

Results. *No traditional cereal–legume food met all complementary food macronutrient requirements on its own. Cereal–legume blends made with peanut or cowpeas were low in quality protein, while those with soybean were low in fat. Lysine was the limiting amino acid (PDCAAS 0.50 to 0.82) in all blends. Adding lysine increased utilizable protein by 1% to 10% in soybean blends, 35% to 40% in peanut blends, and 14% to 24% in cowpea blends. Peanut–maize, peanut–millet, and all soybean–cereal blends were able to meet macronutrient targets; most micronutrients remained below recommended levels.*

Conclusions. *Traditional cereal–legume blends made from locally available ingredients do not meet energy, quality protein, and fat recommendations for complementary foods; however, such complementary food blends may be optimized to meet nutrient requirements by using linear programming as a tool to determine the exact levels of fortificants to be added (including, but not limited to, added fat, amino acids, and micronutrients).*

Key words: Cereal–legume blend, complementary food, linear programming, protein quality

Introduction

Nutritionally adequate complementary foods are of high priority in developing countries. After 6 months of age, breastmilk is no longer nutritionally sufficient for infants, and nutrient-dense complementary foods must be introduced, which can impact immediate and long-term nutritional status [1]. Traditional complementary foods that are predominantly cereal-based are not nutritionally adequate [2]; in a review of cereal-based complementary foods in developing countries, most failed to meet many micronutrient requirements [3]. In Ghana, for instance, the traditional fermented maize dough-based porridge *koko* has been found to be poor in energy density and protein quality, to lack many micronutrients, and to be implicated in protein–energy malnutrition [4]. In a technical meeting convened by the World Health Organization (WHO) and UNICEF in 1998, the need to examine the evidence for effective interventions to improve complementary foods and feeding practices was emphasized, and WHO has outlined a comprehensive set of guiding principles for appropriate feeding of breastfed infants [1]. Traditionally made cereal–legume blends have a better nutritional profile than solely cereal-based complementary

Devika J. Suri is affiliated with the Nevin Scrimshaw International Nutrition Foundation, Boston, Massachusetts, USA; Kwaku Tano-Debrah is affiliated with the Department of Nutrition and Food Science, University of Ghana, Accra; Shibani A. Ghosh is affiliated with the Friedman School of Nutrition Science and Policy, Tufts University, and the Nevin Scrimshaw International Nutrition Foundation, Boston.

Please direct queries to the corresponding author: Devika Suri, 150 Harrison Ave., Boston, MA 02111, USA; e-mail: dsuri@inffoundation.org.

foods; however, they are still lacking in essential nutrients, including fat, iron, zinc, and calcium [3]. A lower fat value leads to poor energy density, a significant concern in the 6- to 24-month-old population. Furthermore, although these are likely to form complete (complementary) proteins, they have not been assessed for macronutrient quality. The USAID Food Aid Quality Review project performed an extensive review to identify key needs and recommendations for improving the quality of food aid products (including cereal–legume blends), programs, and priorities. Some key recommendations for improving nutritional value were to improve the formulation of existing fortified blended food products (such as cereal–legume blends that are fortified with micronutrients), upgrade the vitamin and mineral mixes used, as well as develop or adopt non-cereal-based (e.g., lipid-based) products for management of nutritional deficiencies [5].

Emerging evidence indicates that macronutrient balance could play a key role in the prevention and treatment of malnutrition as well as improve developmental and cognitive outcomes. Efficacy studies in Malawi have shown higher recovery rates from moderate acute malnutrition with the use of supplementary foods such as lipid-based nutrient supplements (high fat and high protein) compared with the traditional corn–soybean blend (CSB) (without added fat or milk protein). In a clinical effectiveness trial, moderately wasted children given lipid nutrient supplements (soybean- and peanut-based versus milk- and peanut-based) had similar recovery rates. Children receiving the lipid nutrient supplements were more likely to recover than those receiving fortified CSB (only micronutrients added) [6]. A more recent study examined the efficacy of the fortified CSB++ with that of two ready-to-use supplementary food products (like lipid-based peanut supplements, these were energy-dense pastes) for the treatment of moderate acute malnutrition in rural Malawian children aged 6 to 59 months. The study found that the recovery rate for the group receiving CSB++ (763 of 888, 85.9%) was similar to that for the group receiving a soybean- and lipid-based supplement (95 of 806, 87.7%) and for the group receiving a soybean-, whey-, and lipid-based supplement (807 of 918, 88%). Although children who received CSB++ required 2 days longer to recover and had a lower rate of weight gain as compared with the groups receiving the other two products, the height gain was the same for all three groups [7]. A trial comparing the development of 18-month-old infants receiving complementary foods for 1 year (either 25 g or 50 g of lipid-based nutrient supplements or 71 g of a micronutrient-fortified CSB porridge called *Likuni Phala*) found that at 18 months of chronological age, there were no significant differences among the three treatment groups in mental age, mean raw developmental score, and developmental quotient [8].

Clearly, given the current recommendations to improve existing blended products and the mounting evidence around improved blended products as supplementary foods, it would be important to consider both the macronutrient balance (ratios between protein, energy and fat) and the micronutrient levels of existing traditional complementary foods. Within the formulation of fortified blended food products, the 2011 Food Aid Quality Review (FAQR) report [5] recommends the addition of a dairy source of protein to products consumed by children 6 to 24 months of age, pregnant and lactating women, wasted children, and wasted individuals undergoing treatment for HIV/AIDS. Furthermore, it recommends the development of new forms of fortified blended food products (e.g., alternative grains and vegetable protein sources) and the exploration of ways to reduce phytates, which inhibit iron and zinc absorption. Although the addition of skim milk powder and/or whey protein will improve the protein quality and nutrient density of cereal–legume blends, this strategy could increase the cost of such blends by about 70% [9]. Another possible consideration is the reformulation of cereal–legume blends to provide energy by the addition of fat and small amounts of sugar in order to achieve energy balance. This, however, might remove some cereal or legume fractions and thus modify protein quality. The addition of essential amino acids to the micronutrient premix that would be added to such products (containing cereals, legumes, and fats) could, however, serve as an alternative strategy to improve energy ratios while maintaining protein quality and protein–energy ratio. For example, lysine, which is a key limiting amino acid [10, 11], is needed in small quantities to improve the quality of the protein in a cereal- and legume-based complementary food. Incorporating the amino acids in the premix allows improvement of protein quality per kilocalorie of food and reduces the amount of excess nitrogen, which is inefficient to metabolize [9].

The cereal–legume blends common in Ghana have not been evaluated against the recommended nutrient composition of complementary foods for breastfed children [12] and the WHO protein and amino acid requirements [13]. Linear programming is a tool that has been used successfully to evaluate and formulate complementary foods and children's diets [14–16], using locally available foods to create optimal diets that meet nutritional requirements. This study had two objectives: to evaluate the nutritional value of some common Ghanaian traditional and cereal- and legume-based complementary foods based on the proposed complementary food composition and revised protein and amino acid requirements for breastfeeding children aged 12 to 24 months; and to utilize linear programming to optimize the macronutrient ratio of these foods using locally available, traditionally accepted and used Ghanaian ingredients and free essential amino acids (i.e., lysine) based on the Protein Digestibility Corrected Amino Acid Score (PDCAAS) method and the protein–energy ratio.

Methods

The linear programming method employed by Briend et al. [14] was used to formulate and optimize the macronutrient ratios of cereal–legume blends for complementary feeding based on six locally available cereals and legumes in Ghana: whole maize, millet, sorghum, soybean, peanut, and cowpea. A nutrient database was created with the use of this method, and a food basket was designed to calculate the nutritional value of its contents with the use of Microsoft Excel (2003). The Solver function in Excel was then utilized for the optimization of the ingredients in the food basket with respect to specific constraints, as described in more detail below. The macronutrient ratios of the blends considered different sources of fat, carbohydrate, and essential amino acids. The cereal–legume blends and koko (a predominant complementary food in Ghana containing only cereals and sugar) were evaluated for nutrient density prior to the optimization. The energy content and palatability of the blends were improved with the addition of a local fat (palm oil) and sugar. The protein quality of the blends was standardized by using different levels of the legumes and also adding calculated amounts of the amino acid lysine, which was used to improve the protein quality while maintaining the protein–energy ratios. Micronutrient content was evaluated in the final complementary food blend to identify insufficiencies and determine the amount that would need to be added.

Nutrient calculations in the food basket were performed using data from the USDA Nutrient Database (USDA NDB numbers for raw, whole foods: maize 20014, millet 20031, sorghum 20067, soybean 16108, peanut 16087, and cowpea 16062) [17]. Protein digestibility values were obtained from the WHO/Food and Agriculture Organization (FAO) standards [10, 13]. The revised amino acid requirements for children 12 to 24 months of age published by WHO/FAO in 2007 [13] were used as the guideline for estimating protein quality of the complementary food formulation.* Utilizable protein was calculated using the PDCAAS method described by WHO [13] and was used in place of total protein when evaluating the protein content of each complementary food blend.

In this example, we used the recommended complementary food composition for children 12 to 24 months of age [12], which assumes average breastmilk intake and consumption of other family foods in addition to this specially prepared complementary food (**table 1**) [18]. The linear programming model was thus set to include the following targets: a daily ration of 60 g dry weight, 264 kcal, 4 to 6.5 g of protein (with a range of 6% to 10% protein–energy ratio) and 8.2 to 11.7 g of fat. The four amino acids used to calculate PDCAAS (lysine, sulfur amino acids, threonine, and tryptophan) were aimed to be equal or greater than the recommended scoring pattern of milligrams of amino acid per gram of protein [13]. Legume composition was kept at less than 25% for palatability and consistency, and sugar was added for palatability but kept under 10% of the total formulation as per recommendations [12]. There was no constraint put on cereal or oil content. A list of the targets and constraints used in the linear programming model is shown in **table 2**.

* Scoring pattern (mg/g protein requirement): Lys, 52; sulfur amino acids, 26; Thr, 27; Trp, 7.4.

TABLE 1. Daily ration nutrient recommendations for a complementary food based on average breastmilk consumption among children 12 to 24 months of age

Component/nutrient	Recommended amount
Total complementary food amount dry weight (g)	60
Energy (kcal)	264
Energy from protein (protein–energy ratio) (%)	6–10
Energy from lipid (%)	28–40[a]
Energy from carbohydrate (%)	62–66
Carbohydrate (g)	41–43.5
Protein (g)	4–6.5
Fat (g)	8.2–11.7[a]
Vitamin A (µg RE)	300
Biotin (µg)	1.74
Choline (mg)	54
Folic acid (µg)	49.8
Niacin (mg)	1.9
Panthothenic acid (mg)	0.38
Riboflavin (mg)	0.15
Thiamine (mg)	0.18
Vitamin B_6 (mg)	0.21
Vitamin B_{12} (µg)	0.32
Vitamin C (mg)	50–100
Vitamin D (µg)	1–2
Vitamin E (mg)	5
Calcium (mg)	100–200
Copper (µg)	200–400
Iodide (µg)	90
Iron (mg)	7
Magnesium (mg)	40–60
Manganese (mg)	0.6
Phosphorus (mg)	75–100
Selenium (µg)	10
Zinc (mg)	4–5

RE, retinol equivalents

a. Upper end of range taken from Uauy et al. [18].

TABLE 2. Linear programming targets and constraints

Variable	Constraint
Total weight (g)	60
Calories (kcal)	264[a]
Protein (g)[b]	≥ 6.5
Tryptophan (mg/g protein)	≥ 8.5[c]
Threonine (mg/g protein)	≥ 31[c]
Lysine (mg/g protein)	≥ 57[c]
Sulfur amino acids (mg/g protein)[d]	≥ 28[c]
Protein–energy ratio	6%–10%
Fat (g)	8.2–11.7
Sugar	≤ 10%
Legume	≤ 25%

a. Linear programming "target" goal.
b. Utilizable protein, based on protein quality using the Protein Digestibility Corrected Amino Acid Score (PDCAAS) method.
c. Amino acid score ≥ 1.
d. Cysteine and methionine.

Each cereal was paired with each legume, resulting in nine cereal–legume combinations (soybean–maize, soybean–millet, soybean–sorghum, peanut–maize, peanut–millet, peanut–sorghum, cowpea–maize, cowpea–millet, cowpea–sorghum); koko was included for comparison. The combinations were individually entered into the linear programming model in Excel, and the contents of macronutrients, micronutrients, and amino acids were evaluated. In the first stage, each cereal was set at 80% and each legume at 20% to provide a baseline comparison between blends. The koko recipe included 80% maize and 20% sugar (equating to 48 g of maize and 12 g of sugar in a 60-g dry ration). In the second stage, the Excel Solver function was used to optimize each cereal–legume blend with oil and sugar available in the food basket, with the same goals and constraints as before. In the third stage, the nine cereal–legume combinations were run again with the same constraints, but in addition to fat and sugar, lysine was made available to the linear programming food basket to improve protein quality and increase utilizable protein, and was added up to the point that the amino acid score of lysine reached 1.0 and no other amino acid became limiting. The rationale for incorporating lysine as the free essential amino acid was that this was the only amino acid that was limiting if legume levels were reduced in all nine cereal–legume combinations. The final nine blends from the third stage of linear programming optimization were evaluated against macronutrient and micronutrient requirements for the 12- to 24-month age group.

Results

The baseline nutrient contents of cereal–legume combinations (80% cereal, 20% legume) and koko (80% maize, 20% sugar) are shown in **table 3**. Cereal–peanut

TABLE 3. Baseline nutrient contents of 80% cereal–20% legume combinations and koko (per 60-g ration)

Mixture	Cereal (%)	Legume (%)	Sugar (%)	Energy (kcal)	Protein (g)	Utilizable protein (g)[a]	Fat (g)	PE ratio	Lowest AA score[b]	Limiting AA	PDCAAS
Soybean–maize	80	20	0	229	8.9	7.7	4.6	13.5	0.99	None	0.87
Soybean–millet	80	20	0	235	9.7	7.2	4.4	12.2	0.88	Lysine	0.74
Soybean–sorghum	80	20	0	216	9.8	7.4	4.0	13.6	0.88	Lysine	0.75
Peanut–maize	80	20	0	243	7.6	4.1	8.2	6.7	0.61	Lysine	0.54
Peanut–millet	80	20	0	249	8.4	3.6	7.9	5.7	0.50	Lysine	0.42
Peanut–sorghum	80	20	0	231	8.5	3.7	7.5	6.5	0.51	Lysine	0.44
Cowpea–maize	80	20	0	216	7.3	4.9	2.4	9.2	0.82	Lysine	0.67
Cowpea–millet	80	20	0	222	8.1	4.4	2.2	8.0	0.69	Lysine	0.54
Cowpea–sorghum	80	20	0	203	8.2	4.6	1.7	9.1	0.69	Lysine	0.56
Koko	80	0	20	222	4.5	2.1	2.3	3.8	0.54	Lysine	0.46

AA, amino acid; PDCAAS, Protein Digestibility Corrected Amino Acid Score; PE, protein–energy
a. Lysine always had the lowest amino acid score unless otherwise specified.
b. Adjusted for digestibility and quality by the PDCAAS method.

and cereal–cowpea blends were low in utilizable protein (3.6 to 4.9 g), with lysine as the limiting amino acid (amino acid score 0.50 to 0.82). Koko contained the least utilizable protein (2.1 g), with a lysine score of 0.54; the only other amino acid with a score less than 1 was tryptophan, with a score of 0.96. All peanut–cereal blends contained adequate fat (8 g), whereas cowpea–cereal blends had the lowest fat content (2 g). Soybean–cereal blends met protein requirements but were deficient in fat (< 4.6 g), with protein–energy ratios above recommended levels (12% to 14%). None of the cereal–legume mixtures or koko provided adequate calories when constrained to a 60-g dry portion size (216 to 249 kcal). The total protein content, unadjusted for amino acid quality and digestibility, overestimated effective utilizable protein in the mixtures by up to twofold in the peanut–millet combination (**fig. 1**). Total protein overestimated utilizable protein the least in the soybean–maize blend, by 16%.

Table 4 presents the results of the second stage with the addition of oil and sugar to the linear programming food basket. After optimization of the model, soybean–maize was the only combination to meet the constraints with the addition of only oil and sugar. Although the peanut–maize blend met total protein requirements, it had a very low PDCAAS (0.56), which reduced effective utilizable protein from 7.4 to 4.1 g. The soybean–millet and soybean–sorghum optimized combinations met every constraint except for protein–energy ratio, which was 11.4 for both. All other combinations were deficient in energy (< 264 kcal), and lysine remained the limiting amino acid, with scores ranging from 0.52 to 0.90. However, most of the second-stage combinations did meet protein–energy ratio and fat constraints after the addition of oil and sugar. Koko was able to meet fat requirements with the addition of oil, but utilizable protein and protein–energy ratio remained low (2.1 g and 3.3, respectively).

The results of the third stage, in which lysine was added to the Solver function, are shown in **table 5**. Adding lysine improved protein quality and increased utilizable protein by 1% to 10% in soybean blends, 35% to 40% in peanut blends, and 14% to 24% in cowpea blends. The combinations with soybean required very little additional lysine to improve the score to 1.0, ranging from 0.02% to 0.06% of the final blend weight. Koko remained deficient in utilizable protein (3.7 g), even with addition of lysine, which was only brought up to a score of 0.96, that of tryptophan, the next limiting amino acid. Target complementary food macronutrient composition and ratio were achieved in five optimized combinations with the addition of oil, sugar, and/or lysine: peanut–maize, peanut–millet, and all soybean–cereal blends. However, in these five combinations, most micronutrients, including calcium, iron, zinc, folic acid, vitamin B_{12}, and vitamin A, did not meet recommended levels (**table 6**).

Discussion

The first objective of this study was to evaluate the macronutrient contents of potential complementary food blends of common Ghanaian cereals and legumes, as well as koko (a traditional weaning food made from fermented maize dough and sugar), based on the proposed complementary food composition and revised amino acid requirements for breastfed children aged 12 to 24 months [12]. Koko did not meet the recommended complementary food nutrient density, nor did it meet the recent WHO/FAO protein and amino acid requirements for this age group. Blends containing maize, millet, or sorghum as cereals and cowpea, peanut, or soybean as legumes had improved protein quality, energy, and micronutrients compared with koko but still did not meet all nutrient recommendations for complementary foods.

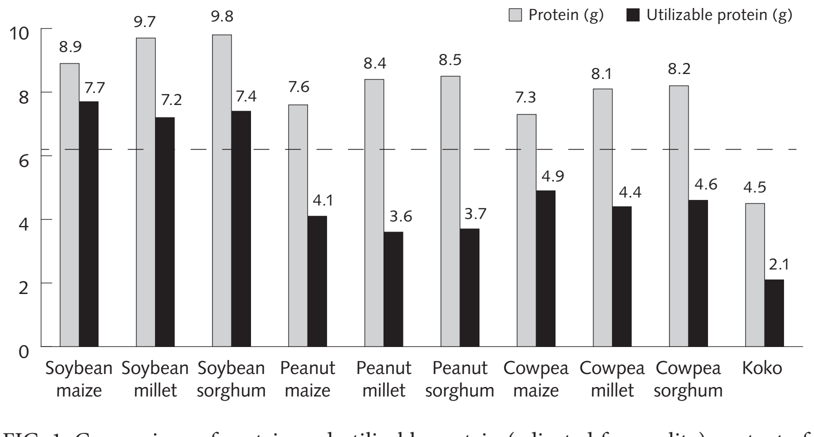

FIG. 1. Comparison of protein and utilizable protein (adjusted for quality) content of 80%/20% cereal–legume blends and koko; target of 6.5 g

TABLE 4. Nutrient contents of cereal–legume combinations optimized with oil and sugar (given as percentage of dry weight of 60-g ration) and koko — results of second stage of linear programming

Mixture	Cereal (%)	Legume (%)	Oil (%)	Sugar (%)	Energy (kcal)	Protein (g)	Utilizable protein (g)	Fat (g)	PE ratio	Lowest AA score	Limiting AA	PDCAAS
Soybean–maize	66	17	11.5	5	264	7.5	6.6	10.9	10.0	1.00	None	0.88
Soybean–millet	58	23	9	10	264	8.8	7.5	9.6	11.4	1.00	None	0.85
Soybean–sorghum	54	23	13.2	10	264	8.6	7.5	11.7	11.4	1.01	None	0.87
Peanut–maize	60	26	4	10	264	7.4	4.1	11.7	6.3	0.63	Lysine	0.56
Peanut–millet	75	25	0	0	255	8.8	4.0	9.3	6.2	0.52	Lysine	0.45
Peanut–sorghum	59	25	4.9	10	257	8.0	3.9	11.7	6.0	0.55	Lysine	0.48
Cowpea–maize	65	25	10.3	0	247	7.2	5.3	8.2	8.5	0.90	Lysine	0.73
Cowpea–millet	64	25	10.6	0	253	7.8	4.8	8.2	7.6	0.79	Lysine	0.62
Cowpea–sorghum	64	25	11.2	0	240	7.9	5.0	8.2	8.3	0.79	Lysine	0.63
Koko	80.1	0	9.9	10	251	4.5	2.1	8.2	3.3	0.54	Lysine	0.46

AA, amino acid; PDCAAS, Protein Digestibility Corrected Amino Acid Score; PE, protein–energy

TABLE 5. Nutrient contents of cereal–legume combinations optimized with oil, sugar, and lysine (given as percentage of dry weight of 60-g ration) and koko—results of third stage of linear programming

Mixture	Cereal (%)	Legume (%)	Oil (%)	Sugar (%)	Lysine (%)	Energy (kcal)	Protein (g)	Utilizable protein (g)	Fat (g)	PE ratio	Lowest AA score	Limiting AA	PDCAAS
Soybean–maize	71	16	12	2	0.02	264	7.5	6.5	11.0	9.8	1.00	None	0.87
Soybean–millet	63	17	10	10	0.06	264	7.9	6.6	9.5	10.0	1.00	None	0.84
Soybean–sorghum	59	17	14	10	0.05	263	7.7	6.6	11.7	10.0	1.00	None	0.85
Peanut–maize	61	25	5	10	0.21	264	7.4	6.5	11.7	9.9	1.00	None	0.88
Peanut–millet	76	18	6	0	0.29	264	8.0	6.6	10.7	10.0	1.00	None	0.83
Peanut–sorghum	61	21	7	10	0.26	258	7.6	6.4	11.7	10.0	0.99	None	0.84
Cowpea–maize	65	25	10	0	0.05	247	7.2	5.9	8.2	9.5	1.00	None	0.81
Cowpea–millet	64	25	11	0	0.11	253	7.8	6.1	8.2	9.7	1.00	None	0.78
Cowpea– sorghum	62	25	13	0	0.11	246	7.8	6.1	9.3	10.0	0.99	None	0.79
Koko	80	0	9.9	10	0.14	251	4.6	3.7	8.2	5.9	0.96	Lys/Trp	0.80

AA, amino acid; PDCAAS, Protein Digestibility Corrected Amino Acid Score; PE, protein–energy

TABLE 6. Nutrient contents of five cereal–legume combinations optimized through linear programming[a]

Nutrient	Recommended amount	Soybean–maize	Soybean–millet	Soybean–sorghum	Peanut–maize	Peanut–millet
Total dry weight (g)	**60**	**60**	**60**	**60**	**60**	**60**
Energy (kcal)	**264**	**264**	**264**	**263**	**264**	**264**
Utilizable protein (g)	**6.5**	**6.5**	**6.6**	**6.6**	**6.5**	**6.6**
Fat (g)	**8.2–11.7**	**11**	**9.5**	**11.7**	**11.7**	**10.7**
PE ratio	**6–10**	**9.8**	**10**	**10**	**9.9**	**10**
Vitamin A (μg RE)	**300**	2.4	0.1	0.1	2.0	0.0
Choline (mg)	**54**	10.98	11.63	11.70	7.78	5.72
Folic acid (μg)	**49.8**	0.00	0.00	0.00	0.00	0.00
Niacin (mg)	**1.9**	1.68	**1.95**	1.19	**3.10**	**3.46**
Panthothenic acid (mg)	**0.38**	0.25	**0.40**	0.08	**0.42**	**0.58**
Riboflavin (mg)	**0.15**	**0.17**	**0.21**	0.13	0.09	**0.15**
Thiamine (mg)	**0.18**	**0.25**	**0.24**	0.16	**0.23**	**0.25**
Vitamin B_6 (mg)	**0.21**	**0.29**	0.19	0.04	**0.26**	**0.21**
Vitamin B_{12} (μg)	**0.32**	0.00	0.00	0.00	0.00	0.00
Vitamin C (mg)	**50–100**	0.57	0.60	0.60	0.00	0.00
Vitamin D (μg)	**1–2**	0.00	0.00	0.00	0.00	0.00
Vitamin E (mg)	**5**	1.43	1.05	1.44	1.84	1.47
Calcium (mg)	**100–200**	29.17	30.85	37.87	16.22	13.64
Copper (μg)	**200–400**	0.29	0.47	0.17	0.27	0.48
Iodide (μg)	**90**	2.63	2.72	3.14	1.67	1.87
Iron (mg)	**7**	2.63	2.72	3.14	1.67	1.87
Magnesium (mg)	**40–60**	**80.3**	**71.4**	**129.7**	**71.0**	**70.2**
Manganese (mg)	**0.6**	0.44	**0.87**	0.25	0.46	**0.95**
Phosphorus (mg)	**75–100**	**155.6**	**178.9**	**194.71**	**132.0**	**170.7**
Selenium (μg)	**10**	8.25	2.81	1.79	6.70	2.01
Zinc (mg)	**4–5**	1.40	1.14	0.49	1.29	1.13

PE, protein–energy; RE, retinol equivalents

a. Values of nutrients meeting recommended levels are shown in boldface.

The second objective was to utilize linear programming to optimize the cereal–legume blends with the addition of other ingredients to improve energy balance and maintain macronutrient ratio while improving protein quality. It was found that it is possible to achieve optimal complementary foods that meet energy and macronutrient requirements through the reformulation of the traditional complementary food blend. In this study, improvements in energy balance were achieved by the addition of fat (palm oil) and sugar (keeping to less than 10% of the total mixture), while improvements in protein quality were sought using the essential amino acid, lysine. Out of the nine cereal–legume combinations, optimization of macronutrients and macronutrient ratios was achieved in five: maize–soybean, millet–soybean, sorghum–soybean, maize–peanut, and millet–peanut blends. However, even with the addition of oil, sugar, and lysine, the other combinations could not be optimized to meet recommended macronutrient levels for a complementary food.

Most micronutrients remained below recommended quantities in all optimized combinations, with the exception of magnesium. This was expected, as certain nutrients, including calcium, iron, zinc, and vitamin B_6, have been found lacking in most traditional complementary foods [3, 4, 19], and to meet the recommended micronutrient contents these blends would need to be fortified. Although the overall fat content of optimized blends met recommended levels, a caveat of this study is that assessment of the adequacy of essential fatty acids was not conducted. This will need to be considered in future formulations and/or assessments of the essential fatty acid contents of complementary foods.

Although there is an emphasis on micronutrient adequacy in the complementary food literature, less attention has been paid to the importance of protein quality during early growth and development. In a review of complementary foods in several developing countries, Lutter and Rivera noted the lack of data on macronutrient composition of complementary foods, citing the importance of essential fatty acids and overall lipids in the diet [19]. They also noted that although protein intake from complementary foods appeared adequate, there is little attention to protein quality in the studies they reviewed. Gibson et al. [3] found that energy and protein needs were mostly met by the complementary food blends evaluated in their study, but they did not adjust for protein quality. In our evaluation of nine cereal–legume blends and koko, they all appeared to have adequate protein; however, after adjustment for PDCAAS, the resulting utilizable protein levels were lower by 1.2 to 4.8 g (an overestimation of protein content of 16% to 133%).

A recent workshop emphasized the growing evidence for the role of protein and amino acids in young child growth and development [20, 21]. Protein intake in infancy stimulates growth, and there is a strong positive association between protein intake at 9 months of age and later height and weight [9]. Improvement of dietary protein quality by the introduction of higher-quality protein varieties of maize has had positive effects on growth in children in studies conducted in Africa, Asia, and Latin America [22]. Furthermore, individual amino acids (lysine and arginine) have been associated with linear growth [23], and above and beyond the benefits of improved protein quality, lysine has been associated with reductions in diarrheal episodes and stress indicators [24–26]. Another consideration for protein requirements is the need for increased protein during infection and recovery and in energy deficit [13]. Infants and young children in developing countries can suffer from multiple infections per year, each lasting for 1 to 2 weeks [27], which will increase protein and lysine requirements [28, 29]. A diet that is moderately deficient in energy (5% below requirement) can increase protein needs by 10% [30]. Thus, a complementary food blend that helps a child meet his or her daily energy requirements and has additional lysine will improve utilizable protein to meet increased needs. In addition, the macronutrient balance achieved in the optimized blends may be important in the prevention of stunting: in a study of different types of fortified complementary food, including sprinkles, Nutritabs, and energy-dense, fat-based Nutributter, all had positive effects on motor development in children 6 to 12 months of age, but only Nutributter positively affected growth [31].

Addition of dried skim milk or whey protein to complementary foods to improve both protein and micronutrient contents has been recommended [9]. The use of lysine in the quantities found by the linear programming models in this study could be an alternative strategy, especially where cost and logistic issues arise during implementation. That being said, although studies have shown an association between cow's milk and linear growth [32], no study has compared a complementary food with a dairy protein source versus one with lysine using linear growth as an outcome.

Clearly, there are limitations in the interpretation of the findings of this study. First, although linear programming could also be used to develop formulations that would meet the needs of quality protein and fat without added amino acids, we have not tested that approach. Addressing other alternative strategies (e.g., multiple legume combinations, fish protein concentrates, dried meat protein) was beyond the scope of this study, and this is a potential caveat. First of all, this evaluation of complementary foods was based on the recommended nutrient densities for children 12 to 24 months of age consuming average amounts of breastmilk and did not take into account different levels of breastmilk intake, which will alter requirements [1]. Ideally, the amount of complementary foods given to a child would be in proportion to how much breastmilk the child receives and would provide the necessary nutrients lacking from low breastmilk intake; this would be an important point to evaluate in future research. Second, antinutrients such as phytic acid found in cereals and legumes can reduce the absorption of nutrients, including iron, zinc, and calcium [33], and were not taken into account in this complementary food model. Processing and cooking methods that would increase bioavailability were also not evaluated. However, the bioavailability of protein was adjusted for in the linear programming model by attributing the estimated protein digestibility value of each ingredient. Finally, this was a theoretical exercise to show how combinations of cereals and legumes might or might not be able to meet macronutrient requirements of complementary foods with the addition of particular amounts of oil, sugar, and lysine. Based on these findings, further work is ongoing in the development and testing (sensory and efficacy testing) of a complementary food supplement (macronutrient and micronutrient balanced) that would be added to koko. Further studies need to be conducted to examine the efficacy of such a blended product in improving growth and development in this population before considering it as an alternative strategy.

Conclusions

Traditional Ghanaian koko and cereal–legume blends did not meet complementary food nutrient density recommendations for young children between 12 and 24 months of age. This study found that total protein content, unadjusted for quality and digestibility, resulted in overestimation of utilizable protein by as much as 133%, even in cereal–legume blends. Especially in cases of malnutrition and infection, when protein needs increase, protein quality and utilizable protein should be considered when evaluating complementary foods. With linear programming, it was possible to achieve optimal complementary food blends that met energy and macronutrient requirements by the addition of other ingredients, including oil, sugar, and lysine, but micronutrients for the most part remained deficient and would need to be supplemented. This study demonstrates the importance of evaluating the nutritional content of complementary food blends, especially taking protein quality into account, and shows that complementary foods can be optimized using linear programming as a tool to determine the level of fortificants and locally available foods needed to meet requirements. Further areas of research include examining the variation in meeting nutrient needs of this population using different sources of protein (e.g., addition of single versus multiple amino acids, use of dairy protein, other animal-source protein, or other legume protein). The efficacy and effectiveness of such complementary food formulations in addressing the nutrient needs of young children in developing countries and improving growth and development in these populations need to be investigated.

Conflicts of interest

This research project was funded by Ajinomoto Co., Inc., as part of an ongoing public–private partnership.

References

1. Brown KH, Dewey KG, Allen LH. Complementary feeding of young children in developing countries: a review of current scientific knowledge. World Health Organization 1998.
2. Treche S, Mbome IL. Viscosity, energy density and osmolality of gruels for infants prepared from locally produced commercial flours in some developing countries. Int J Food Sci Nutr 1999;50:117–125.
3. Gibson RS, Ferguson EL, Lehrfeld J. Complementary foods for infant feeding in developing countries: their nutrient adequacy and improvement. Eur J Clin Nutr 1998;52:764–770.
4. Williams C. A nutritional disease of childhood associated with a maize diet. Arch Dis Child 1933;8:423–433.
5. Webb P, Rogers B, Rosenberg I, Schlossman N, Wanke C, Bagriansky J, Sadler K, Johnson Q, Tilahun J, Reese-Masterson A, Narayan A. Delivering improved nutrition: recommendations for changes to U.S. food aid products and programs. Tufts University, Boston, MA; 2011.
6. Matilsky DK, Maleta K, Castleman T, Manary MJ. Supplementary feeding with fortified spreads results in higher recovery rates than with a corn/soy blend in moderately wasted children. J Nutr 2009;139:773–778.
7. LaGrone LN, Trehan I, Meuli GJ, Wang RJ, Thakwalakwa C, Maleta K, Manary MJ. A novel fortified blended flour, corn-soy blend "plus-plus," is not inferior to lipid-based ready-to-use supplementary foods for the treatment of moderate acute malnutrition in Malawian children. Am J Clin Nutr 2012;95:212–219.
8. Phuka JC, Gladstone M, Maleta K, Thakwalakwa C, Cheung YB, Briend A, Manary MJ, Ashorn P. Developmental outcomes among 18-month-old Malawians after a year of complementary feeding with lipid-based nutrient supplements or corn-soy flour. Matern Child Nutr 2012;8:239–248.
9. Hoppe C, Andersen GS, Jacobsen S, Molgaard C, Friis H, Sangild PT, Michaelsen KF. The use of whey or skimmed milk powder in fortified blended foods for vulnerable groups. J Nutr 2008;138:145S–161S.
10. FAO/WHO. Protein quality evaluation. Rome: Food and Agriculture Organization; 1991.
11. Young V, Pellett PL. Current concepts concerning indispensable amino acid needs in adults and their implications for international nutrition planning. Nutr Bull 1990;12:289–300.
12. Lutter CK, Dewey KG. Proposed nutrient composition for fortified complementary foods. J Nutr 2003;133:3011S–3020.
13. WHO. Protein and amino acid requirements in human nutrition. Report of a joint WHO/FAO/UNU expert consultation. In WHO Technical Report Series. Geneva: World Health Organization (WHO Technical Report Series, No. 935); 2007.
14. Briend A, Darmon N, Ferguson E, Erhardt JG. Linear programming: a mathematical tool for analyzing and optimizing children's diets during the complementary feeding period. J Pediatr Gastroenterol Nutr 2003;36:12–22.
15. Ferguson EL, Darmon N, Fahmida U, Fitriyanti S, Harper TB, Premachandra IM. Design of optimal food-based complementary feeding recommendations and identification of key "problem nutrients" using goal programming. J Nutr 2006;136:2399–2404.
16. Santika O, Fahmida U, Ferguson EL. Development of food-based complementary feeding recommendations for 9- to 11-month-old peri-urban Indonesian infants using linear programming. J Nutr 2009;139:135–141.
17. U.S. Department of Agriculture ARS. USDA National nutrient database for standard reference. In Release 24. Nutrient data laboratory home page. Available at: http://www.ars.usda.gov/ba/bhnrc/ndl. Accessed 20 June 2014.
18. Uauy R, Castillo C. Lipid requirements of infants: implications for nutrient composition of fortified complementary foods. J Nutr 2003;133:2962S–2972.
19. Lutter CK, Rivera JA. Nutritional status of infants and young children and characteristics of their diets. J Nutr 2003;133:2941S–2949S.
20. Suri D, Marcus S, Ghosh S, Kurpad A, Rosenberg I. Protein quality workshop: importance of protein quality in prevention and treatment of child malnutrition. Food Nutr Bull 2013;34:223–223.
21. Ghosh S. Assessment of protein adequacy in developing countries: quality matters. Food Nutr Bull 2013;34:244–246.
22. Akalu GT, Gunaratna S, Nilupa S, De Groote H. The effectiveness of quality protein maize in improving the nutritional status of young children in the Ethiopian highlands. Food Nutr Bull 2010;31:418–430.
23. van Vught AJ, Heitmann BL, Nieuwenhuizen AG, Veldhorst MA, Andersen LB, Hasselstrom H, Brummer R-JM, Westerterp-Plantenga MS. Association between intake of dietary protein and 3-year-change in body growth among normal and overweight 6-year-old boys and girls (CoSCIS). Public Health Nutr 2010;13:647–653.
24. Ghosh S, Smriga M, Vuvor F, Suri D, Mohammed H, Armah SM, Scrimshaw NS. Effect of lysine supplementation on health and morbidity in subjects belonging to poor peri-urban households in Accra, Ghana. Am J Clin

Nutr 2010;92:928–939.
25. Hussain T, Abbas S, Khan MA, Scrimshaw NS. Lysine fortification of wheat flour improves selected indices of the nutritional status of predominantly cereal-eating families in Pakistan. Food Nutr Bull 2004;25:114–122.
26. Zhao W, Zhai F, Zhang D, An Y, Liu Y, He Y, Ge K, Scrimshaw NS. Lysine-fortified wheat flour improves the nutritional and immunological status of wheat-eating families in northern China. Food Nutr Bull 2004;25:123–129.
27. Black RE, Brown KH, Becker S. Malnutrition is a determining factor in diarrheal duration, but not incidence, among young children in a longitudinal study in rural Bangladesh. Am J Clin Nutr 1984;39:87–94.
28. Kurpad AV, Regan MM, Nazareth D, Nagaraj S, Gnanou J, Young VR. Intestinal parasites increase the dietary lysine requirement in chronically undernourished Indian men. Am J Clin Nutr 2003;78:1145–1151.
29. Kurpad AV, Regan MM, Raj T, Vasudevan J, Kuriyan R, Gnanou J, Young VR. Lysine requirements of chronically undernourished adult Indian men, measured by a 24-h indicator amino acid oxidation and balance technique. Am J Clin Nutr 2003;77:101–108.
30. Kishi K, Miyatani S, Inoue G. Requirement and utilization of egg protein by Japanese young men with marginal intakes of energy. J Nutr 1978;108:658–669.
31. Adu-Afarwuah S, Lartey A, Brown KH, Zlotkin S, Briend A, Dewey KG. Randomized comparison of 3 types of micronutrient supplements for home fortification of complementary foods in Ghana: effects on growth and motor development. J Nutr 2007;86:412–420.
32. Hoppe C, Molgaard C, Michaelsen KF. Cow's milk and linear growth in industrialized and developing countries. Annu Rev Nutr 2006;26:131–173.
33. Lonnerdal B, Sandberg AS, Sandstrom B, Kunz C. Inhibitory effects of phytic acid and other inositol phosphates on zinc and calcium-absorption in suckling rats. J Nutr 1989;119:211–214.