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ORIGINAL ARTICLE

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Innovative optimization of ready to use food for treatment of acute malnutrition

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Abstract

Treatment of acute malnutrition typically requires the provision of ready-to-use food (RUF). Common RUF is effective but expensive, being manufactured from costly ingredients, and shipped worldwide from few global suppliers. I developed a linear programming tool to create RUF optimized for low cost using locally grown crops while maintaining necessary nutritional goals and other constraints. My tool utilizes a database of the nutritional value, price, and water efficiency of suitable ingredients and allows adjustment of constraints, including nutrients, flavour, and crop water efficiency. It is designed to (a) address nutrient requirements conforming to current standards and practice; (b) optimize RUF formulae for low cost using a wide range of ingredients for nutritional value and acceptability improvement; (c) ensure protein quality through protein digestibility corrected amino acid score; and (d) adjust RUF formulae according to locally grown crop selection, local prices, and crop water footprint. The tool creates formulae free of expensive dairy ingredients, ensuring desired protein digestibility corrected amino acid score by automatically balancing proteins with complementary quantities of essential amino acids. Using publicly available data with an application to Nigeria, my tool created RUF formulae suitable for local production using local crops to meet all nutrient requirements at a fraction of the ingredient cost and water footprint of current formulae, demonstrating the tool's effectiveness. Optimization of RUF for low cost using locally grown crops will facilitate local production and reduce ingredient as well as transport costs, so more patients can receive lifesaving treatment.

KEYWORDS

linear programming, malnutrition, optimization, ready to use food

1 | INTRODUCTION

1.1 | Problem

According to United Nations Children's Fund (UNICEF), 16 million children under 5 are affected by severe acute malnutrition (SAM), and nearly half of all child deaths are due to malnutrition. Treatment of acute malnutrition typically requires the provision of ready-to-use foods (RUF), which are paste-like formulae with varying serving sizes and composition for treatment of different forms of malnutrition. Ready-to-use therapeutic food (RUTF) is used to treat SAM, whereas ready-to-use supplementary food (RUSF) is used for moderate acute malnutrition (MAM).

RUF is expensive. The high cost of RUF has been found as the primary reason for donors' inability to meet the basic nutrition needs in developing countries (UNICEF, 2009). First, the cost of RUF ingredients is high. Most commonly used RUF, such as Plumpy'Nut® or Plumpy'Doz®, are manufactured from vegetable oil, peanuts, milk powder, sugar, and micronutrient supplements (Wagh & Deore, 2015). Peanuts and milk powder account for over 50% of RUF mass and for most of the total RUF ingredient cost (UNICEF, 2016). Second, the global supply chain, transport, and logistics for RUF are costly. RUF ingredients are typically shipped to the global manufacturing sites, mainly in France and the United States, and then transported to communities in need (Ahmed et al., 2014). UNICEF analysis of the supply chain of Plumpy'Nut® to Africa shows that air transportation is often required, bringing transportation cost to 39% of RUF landed cost (UNICEF, 2009) and contributing to carbon emissions. Third, intellectual property protection and licensing raise cost. Plumpy'Nut® patent protection

has both constrained global RUF supply and added to RUF price (Bakhsh, 2012; Rao, 2010).

1.2 | Current research

Research confirms that the effectiveness of RUF in treating acute malnutrition is subject to specific nutritional constraints (Bahwere et al., 2014; Bahwere et al., 2016; Oakley et al., 2010; World Food Programme [WFP], UNICEF, & United States Agency for International Development, 2016; Collins, Myatt, & Golden, 1998). Suitable caloric, oil, protein, carbohydrate, fibre, and omega-3/6 contents for recovery from SAM and MAM have been established (Nutriset, 2014; World Health Organization, 2016).

With respect to SAM, some studies have shown that peanut-based RUTF is more effective if it contains 25% milk powder compared with 10% (Oakley et al., 2010). More recently, alternative dairy-free RUTF have been found suitable for SAM patients above 2 years of age (Bahwere et al., 2016; Irena et al., 2015), and a new dairy-free soy-maize-sorghum formula has been successfully tested for acceptability and effectiveness in malnourished patients (Bahwere et al., 2017; Owino, Irena, Dibari, & Collins, 2014). Protein digestibility corrected amino acid score (PDCAAS) ≥95, which is recommended for RUTF (Nutriset, 2014), can be achieved without any dairy content (Food and Agriculture Organization [FAO], 2011).

For MAM recovery, RUSF dairy content is not a mandatory requirement in the updated codex for relief food, which instead requires a PDCAAS above 70% (WFP et al., 2016). New cereal blends, containing only 8% milk powder and milk-free RUF, are effective for MAM recovery (LaGrone et al., 2012).

The widespread use of peanuts in current RUF has been challenged by research indicating that peanuts (groundnuts) make RUF prone to aflatoxin contamination (Duclercq, 2014).

Furthermore, research suggests that sorghum, cocoa powder, almond, and sweet potato may raise acceptability when added to certain RUF (Dibari, El Hadji, Collins, & Seal, 2012; Hathorn, 2013; Weber & Callaghan, 2016). Sorghum has been successfully used to create milk free legume based RUTF of suitable acceptability (Owino et al., 2014).

Finally, the WFP et al. (2016) have recommended essential micronutrient supplements to be added for efficient absorption in malnourished patients for most nutrients. Micronutrients in RUF are usually supplemented by adding a standard micronutrient premix. The amount of each micronutrient added depends on the level of deficit from the base ingredients, losses during processing, and the effects of inherent antinutrients. These factors are important considerations when selecting ingredients for RUF formulation.

1.3 | Research gaps

Most commonly used RUF have not been optimized for cost, nutrients, and local contexts. Research is limited on options to (a) select less-costly RUF ingredients and production options (Briend et al., 2015); (b) enhance RUF nutrient content especially with respect to PDCAAS, omega-3, manganese, and choline (Caron, 2012; FAO, 2011); and (c) determine how alternative ingredients may affect RUF acceptability. Furthermore, although there has been a discussion about the benefits of localizing RUF production close to malnourished patients (Clark & Hobbs, 2015; Komrska, 2012; UNICEF, 2014) and successful introduction of chickpea-based Acha Mum and Wawa Mum in Pakistan (WFP, 2016), there is limited research on adjusting RUF ingredients to the local crop selection and environmental constraints.

Research on cost-effective RUF formulae alternatives and on adjusting RUF formulae to local conditions using linear programming (LP) to optimize RUF formulae has been promising (Amegovu et al., 2013; Briend et al., 2015; Dibari et al., 2012; Levesque, Delisle, & Agueh, 2015; Ryan et al., 2014; Segrè, Liu, & Komrska, 2016; Skau et al., 2014; Weber & Callaghan, 2016), but existing tools are not equipped to ensure protein quality directly, which limits their ability to create alternative dairy-free formulae.

Key messages

- Linear programming helps optimize low-cost RUF meeting constraints, including protein quality, local crop availability, and crop water footprint.
- Optimizing RUF while automatically ensuring PDCAAS creates formulae meeting-required protein quality without costly dairy ingredients.
- Including local crops in optimization can support local production while reducing ingredient and transport costs.
- The linear programming tool allows the inclusion of additional ingredients, prices, nutrients, antinutrients, and constraints. It can be adjusted to optimize different specialized nutritious foods or other food products.
- Testing of the optimized formulae will further refine the constraints used for optimization.

1.4 | Solution

I developed LP optimization tool to create cost-effective locally produced RUF formulae to make RUF more accessible and affordable for malnourished populations.

My proposed LP tool seeks to (a) address necessary nutrient requirements conforming to current standards and practice; (b) optimize RUF formulae for low cost using a wide range of ingredients for nutritional value and acceptability improvement; (c) ensure protein quality through PDCAAS while creating dairy-free formulae; and (d) adjust RUF formulae according to locally grown crop selection, local prices and crop water footprint so as to facilitate local production in proximity to malnourished populations.

Testing of the resulting optimized formulae would create a menu from which local practitioners could select RUF that best suits the needs of their communities. Based on current practice, the production of preventive formulae does not require clinical trials.

Figure 1 shows my proposed RUF development process. My research focuses on the first three steps (shaded in blue colour) in the RUF development process.

2 | METHODS

First, international *crop databases* were surveyed, and a database of ingredients suitable for RUF was built. The ingredient database utilizes publicly available nutrient data from the US Department of Agriculture and price data from the Global Economic Monitor, United Nations Conference on Trade and Development, and Food and Agriculture Organization of the United Nations (FAOSTAT).

For all ingredients, the database includes information about crop nutrient composition, local availability, price, and crop water footprint. All ingredients are used in a form with low water content/activity (dry roast soybeans and peanuts; and flours from cassava, sweet potato, soy, corn, and wheat) to meet moisture constraints and ensure 2-year shelf life as required (World Health Organization, 2016).

Based on nutrient content, availability, price, antinutrient content, and shelf stability, 26 foodstuffs were chosen and included in the ingredient database. To allow for wider use in different settings, provision was made for users to expand the ingredient database by utilizing designated cells in the tool. Inclusion of new ingredients requires the input of the nutritional profile per gram of the ingredient, its price in USD/g, and crop water footprint. As required, users can easily enable/disable ingredients to be considered in optimization.

For each ingredient, the database includes designated cells to input additional nutrients or antinutrients and cells to input additional prices if needed for different contexts. The tool automatically calculates with a provision to constrain for the additional nutrients and/or antinutrients.

Second, the LP tool was created to optimize RUF for low cost and local contexts in compliance with applicable nutrient and formulae composition standards. The solver plugin for Excel was used, as it is easily accessible to new users and has been used to create food products acceptable to patients (Dibari et al., 2012).

The tool is set to consider minimization of cost as the objective. Linear objective function is

$$Y = \sum_{i=1}^{n} b_i B_i,$$

where Y is the total cost of ingredients, b_i is the cost per 1 g of ingredients i, and B_i is the amount of ingredient i.

The tool thus generates the ideal quantity of each ingredient available in the database to minimize the overall cost while meeting established nutritional goals and other constraints. Users can select local ingredients as the input for the tool. The cost per gram of each ingredient and supplement is converted from the price databases. The total nutritional value is automatically calculated by adding together the per gram nutrition of each ingredient multiplied by the quantity of each ingredient used.

Compared with previous RUF optimization efforts (Amegovu et al., 2013; Briend et al., 2015; Dibari et al., 2012; Levesque et al., 2015; Ryan et al., 2014; Segrè, Liu, & Komrska, 2016; Skau et al., 2014; Weber & Callaghan, 2016), the tool includes an expanded range of ingredients for RUF nutrient composition and acceptability improvement.

With respect to acceptability in patients, the tool can be configured to automatically select and include a serving of the lowest-cost acceptability improving ingredient—or a combination of acceptability improving ingredients—such as sorghum, cocoa powder, almond, and sweet potato (Dibari et al., 2012; Hathorn, 2013; Weber & Callaghan, 2016). This function reflects the available albeit limited data on acceptability of alternative ingredient combinations in RUF and on the influence of specific ingredients on RUF acceptability, especially pertaining to local tastes and preferences.

The LP tool includes *novel adjustable constraints* of PDCAAS, micronutrient supplements, and water efficiency.

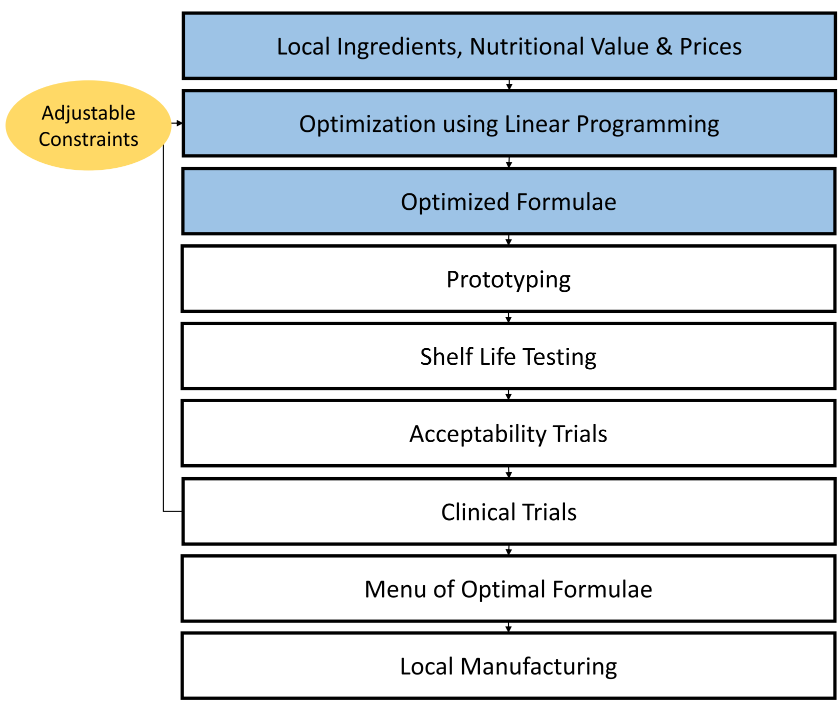

FIGURE 1 Proposed ready-to-use food development process

PDCAAS is automatically calculated and constrained to ensure protein quality (FAO, 2011). PDCAAS is maintained automatically by multiplying the true protein digestibility factor of each ingredient by the quantity of each ingredient and the quantities for essential amino acids within the ingredient according to the US Department of Agriculture nutrition database, adding the protein digestibility-adjusted totals of each amino acid in the formula, and dividing these by the total protein quantity. The resulting values are divided by the respective amino acid quantity per gram of reference protein for children, as determined by the FAO, and constrained to be not less than the desired PDCAAS score. This is expressed by the following two equations:

$$Q_a = \sum_{i=1}^{n} C_i a_i d_i,$$

$$\frac{Q_a}{P} \geq 0.95\,(g_a),$$

where Q_a is total quantity of essential amino acid *a*, C_i is quantity of ingredient *i*, a_i is quantity of amino acid *a* per 1 g of ingredient *i*, d_i is protein digestibility factor of ingredient *i*, *P* is total quantity of protein in the formula, and g_a is goal quantity of amino acid *a* per 1 g reference protein.The tool has two options of constraining for *micronutrient goals*; estimating the composition of a micronutrient supplement premix and minimizing cost of supplements alongside the cost of base ingredients or requiring a certain micronutrient value without supplementation.

In formulae development, the supplement premix will be adjusted following the estimation or analysis of the micronutrient profile of the manufactured RUF to account for loss in processing. For more accurate estimation, the tool allows users to include a percentage loss value for each specified micronutrient. The tool displays the total amounts of each micronutrient for the ingredients used and the expected respective total amounts after processing.

Similarly, amino acid supplementation can be enabled, so that the tool automatically calculates the amounts required for the formulae to meet the target PDCAAS inputted.

The tool also calculates antinutrients for the formulation based on the antinutrient content for each ingredient which can also be enabled/disabled as constraints. For example, the tool includes calculation and constraint for the antinutrient phytate. This antinutrient affects mineral bioavailability and is heat resistant hence not significantly destroyed at the typical processing conditions of ingredients and RUF.

Furthermore, the tool can limit the *water footprint* of ingredients using UNESCO IHE Delft water productivity data for local production in water scarce regions.

The LP tool allows users to set the macro- and micronutrient constraints according to patient condition, creating (a) RUTF formulae suitable for recovery from SAM, SAM with oedema, and/or cirrhosis; (b) RUSF formulae for recovery from MAM; and (c) specialized malnutrition prevention formulae or any kind of food product.

Moreover, the LP tool can modify RUF formulae in response to exogenous changes, such as commodity price shifts and local crop availability.

Figure 2 illustrates the tool's adjustable constraints and optimization process for RUF formulae.

Third, I set *constraints* according to RUTF standards, effective for recovery from SAM, as shown in Table 1 below. These constraints reflect the current WFP, UNICEF, and Nutriset standards, as well as clinical trials of recovery from SAM (Nutriset, 2014, UNICEF, 2009, World Food Programme, 2016). To ensure protein quality, the tool was set to maintain PDCAAS of the formulae greater than or equal to 95 (as in current RUTF) or 100 (FAO, 2011).

Fourth, I used the tool to optimize RUTF formulae for local and international productions, taking Nigeria as a case study for local production.

Case Study: I created an application of the LP tool for Nigeria. I obtained local prices of local ingredients from FAOSTAT, the Nigerian National Bureau of Statistics farmgate, and the Central Bank of

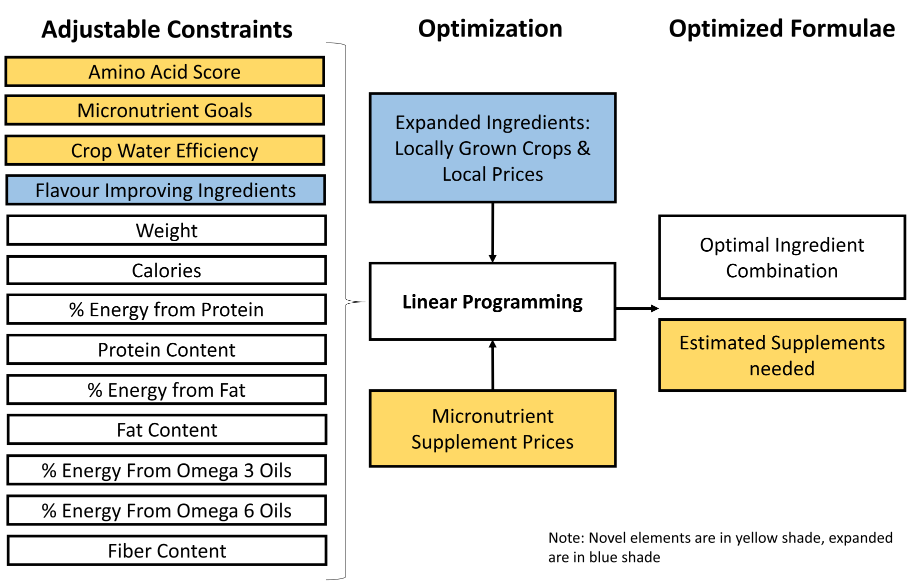

FIGURE 2 Proposed ready-to-use food formulae optimization process

TABLE 1 Nutritional constraints used to generate formulae

Nutrients	Min	Max
Calories	500 kcal	520 kcal
Protein	13 g	16 g
Protein (% energy)	10%	12%
PDCAAS	≥95/100	—
Lipids	26 g	36 g
Lipids (% energy)	45%	60%
Omega-3 fatty acids (% energy)	0.30%	2.50%
Omega-6 fatty acids (% energy)	3%	10%
Fibre content %	—	<5%
Sugar	15 g	18 g
Acceptability improving ingredient servings	≥1	—

Note. Values used determined from Nutriset (2014), UNICEF (2009), and World Food Programme (2016). PDCAAS = protein digestibility corrected amino acid score.

Nigeria. To optimize the local RUTF formulae for Nigeria, I used the 2007 and 2013 price data (the most complete data available) and compared the optimized formulae for these years.

Finally, I compared my optimized RUTF with currently used RUTF for nutrition, ingredient cost, and water efficiency. I calculated the nutritional, ingredient price, and water efficiency value of current RUTF using the same databases as for my optimized international formulae.

3 | RESULTS

Drawing on the ingredient database and on the constraints set, the LP tool generated cost-effective RUF formulae for different circumstances in the international markets and in the local markets in Nigeria. Figure 3 shows the proposed optimized RUTF formulae for international markets (using international trade prices) in 2016 and for Nigeria (using local prices in Nigeria) in 2013 and 2007.

Given the significant crop price differences between the international and Nigerian markets, the proposed optimized RUTF formulae generated by the LP tool differ markedly. Namely, based on international prices in 2016, Formula 1 (PDCAAS ≥ 100) includes soy flour, palm oil, sorghum flour, sugar, and lentil. Formula 2 using Open Market prices for 2016 (PDCAAS ≥ 95) includes roast soybean, palm oil, sorghum flour, sugar, and barley flour. The optimized RUTF formula for Nigeria 2013 consists of palm oil, roast soybean, sugar, cassava flour, cowpea, sorghum flour, and cashew. The optimized formula for Nigeria 2007 includes cowpea, palm oil, sugar, roast soybean, sorghum flour, cashew, and sesame. Sorghum flour was included in all formulae at a serving shown to improve acceptability (Dibari et al., 2012). The tool found sorghum flour more cost effective than other possible acceptability improving alternatives.

The proposed optimized formulae have nutritional values within RUTF requirements set by the WFP, which involve lower ingredient cost and lower water footprint values compared with current practice (Table 2). Considering protein quality, the LP tool successfully created formulae with 100% PDCAAS, possible without individual ingredients with complete proteins by automatically balancing proteins with complementary quantities of the essential amino acids.

The total ingredient cost of the proposed optimized RUTF formulae for international production is below third of the estimated ingredient cost of the currently used Plumpy'Nut® formulae (Figure 4). Ingredient cost reduction in the optimized international formula is largely driven by the replacement of peanuts and milk powder. The main cost savings generated in the local formulae for Nigeria stem from the removal of milk powder, as well as from the low local price of cowpea and soybean.

Water footprint of the proposed optimized formulae is only about one-quarter to one-third of the current formulae (Figure 5). The reduction in water footprint is largely driven by the absence of dairy products in the optimized formulae.

The LP tool was evaluated for accuracy of the predicted nutrient values of RUF formulae. This was done by inputting the ingredient composition of Plumpy'Nut® and one version of Soya-Maize-Sorghum RUTF and comparing the total nutritional values calculated by the tool with the results of laboratory analysis available for Plumpy'Nut® and Soya-Maize-Sorgum RUTF (Bahwere et al., 2016). The tool calculated the caloric value within 1% error of actual laboratory results, estimated the amino acid profile within 3% of actual values, and percent energy from protein within 5% of actual values. Given that these variabilities were within a statistically

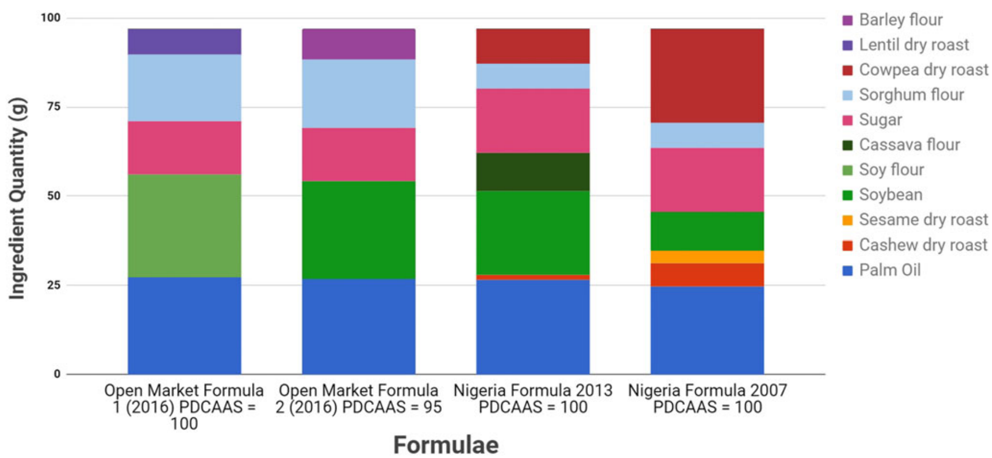

FIGURE 3 Proposed ready-to-use food formulae ingredients. PDCAAS = protein digestibility corrected amino acid score

TABLE 2 Proposed RUF formulae nutrient composition, ingredient price, and water footprint

Formulae	Open market Formula 1 2016 PDCAAS ≥ 100	Open market Formula 2 2016 PDCAAS ≥ 95	Nigeria 2013 formula PDCAAS ≥ 100	Nigeria 2007 formula PDCAAS ≥ 100	Current RUTF (estimates for Plumpy'Nut)
Composition (g) [a][descriptors below table]	Soy flour 28.7 Palm oil 27.3 Sorghum 18.7 Sugar 15 Lentil 7.2	Soybean 27.3 Palm oil 26.9 Sorghum 19.25 Sugar 15 Barley 8.55	Palm oil 26.7 Soybean 23.4 Sugar 18 Cassava 10.7 Cowpea 9.8 Sorghum 7 Cashew 1.7	Cowpea 26.3 Palm oil 24.8 Sugar 18 Soybean 10.9 Sorghum 7 Cashew 6.4 Sesame 3.5	*Peanut* *Sugar* *Milk powder* *Palm oil*
Total weight (g) [excl. supplements]	97	97	97	97	*92*
Total calories	520	520	520	520	*520*
Total protein (g)	13	13	13	13	*13.4*
Total fat (g)	34.34	33.56	32.96	32.77	*34.5*
% Fibre content	35	5	4	5	*<5*
% Energy from Omega-3 fatty acids	0.84	0.79	0.69	0.41	*0.3 to 2.5*
% Energy from Omega-6 fatty acids	9.73	9.69	8.84	8.27	*3 to 10*
PDCAAS	100	95	100	100	*≥95(Plumpy'Nut®)*
Limiting amino acid	None	Lysine	None	None	*Lysine*
Total ingredient price, estimate (USD/serving)	0.04129	0.03813	0.05402	0.0549	*0.14 (Plumpy'Nut®)*
Water footprint (gallons per mt)	3,186.47	3,434.42	3,418.03	5,010.78	*18,159(Plumpy'Nut®)*

Note. Prices calculated using Food and Agriculture Organization and World Bank data. Water footprint calculated using UNESCO-IHE report (Mekonnen & Hoekstra, 2010). Plumpy'Nut® data based on Nutriset (2014) pdf.

[a]Descriptors for USDA nutrient database—soybean: 16111, soybeans, mature, dry roasted; palm oil: 04055, oil, palm; sorghum: 20648, sorghum flour, whole-grain; sugar: sesame: 12023, seeds, sesame seeds, whole, dried; maize: 20017, corn flour, enriched, white; barley: 03181, Babyfood, cereal, barley, dry fortified; cashew: 12085, Nuts, cashew nuts, dry roasted, without salt added. [b]For cassava, only raw forms were available in the US Department of Agriculture nutrient database, so the 11,134, cassava, raw form was converted to a flour by calculation, checked against similar tuber flours and third party sources.

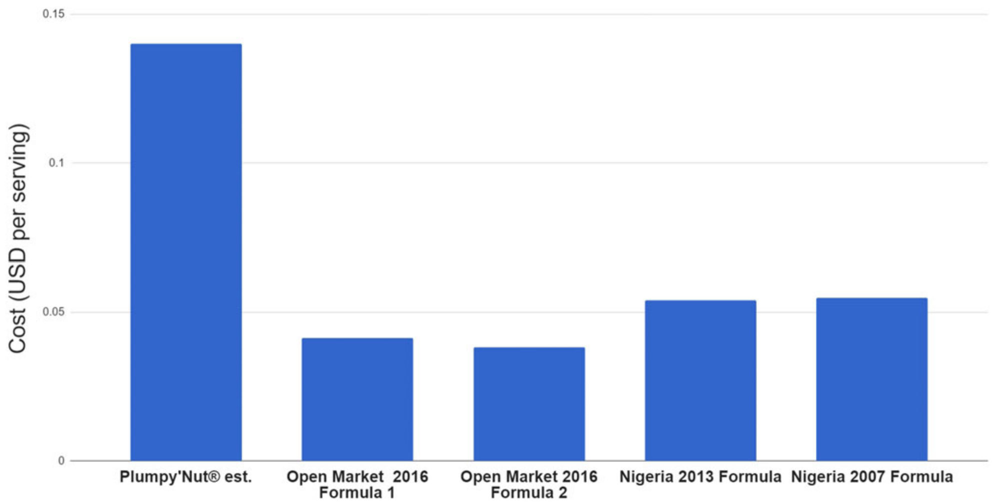

FIGURE 4 Total ingredient cost of formulae

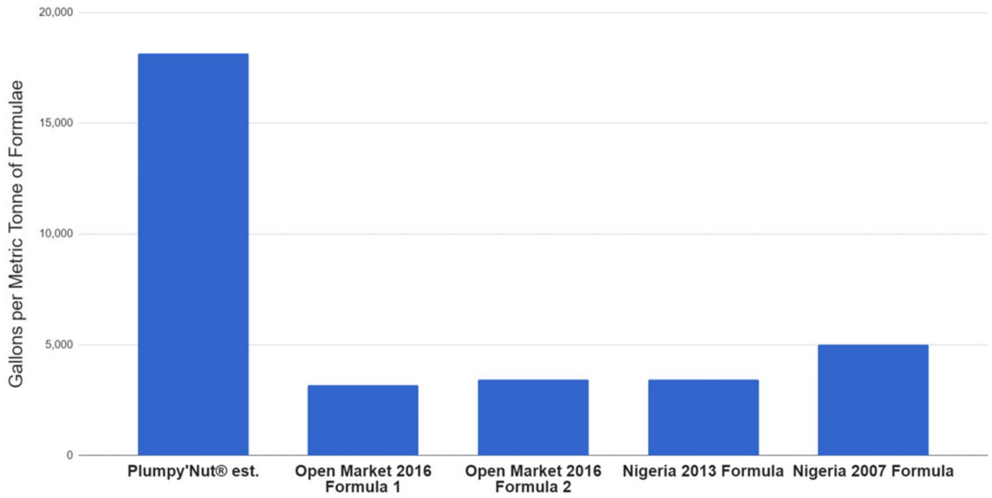

FIGURE 5 Water footprint of formulae

acceptable range, the LP tool was confirmed to accurately predict the nutrient values of RUF formulae.

4 | DISCUSSION AND CONCLUSIONS

My LP tool successfully generated cost-effective RUF formulae applicable for both international and Nigerian local contexts. The tool appropriately utilized an expanded range of ingredients for RUF nutrient composition and the novel adjustable constraints related to amino acid score, flavour-improving ingredients, and crop water footprint. The tool automatically balanced proteins with complementary quantities of essential amino acids. Following on recent success with milk-free formulae, the tool successfully constrained PDCAAS instead of dairy content within the formulae. The lack of true faecal protein digestibility data may, however, limit the accuracy of PDCAAS calculation when including less common ingredients.

By requiring goal protein content, the automatic calculation of PDCAAS allows the LP tool to create formulae with complete amino acid quantities at lower cost than previously achieved. The tool can be easily adjusted to require dairy protein content if needed. Furthermore, the tool is easy to use, allowing simple adjustment of ingredient selection and nutrient constraints.

The software supporting the LP tool can be upgraded to allow for automatic updates in international and local crop price to better support RUF production decisions.

Further testing will help increase the accuracy of the LP tool. Optimized formulae would be verified through laboratory analysis for micronutrient premix development and conformance to the target profile. Further laboratory analysis of manufactured RUF formulae could improve accuracy of estimated micronutrient and antinutrient content. Similarly, testing of the nutrient values of available ingredients will prevent any mistakes due to discrepancies in ingredient nutritional value compared with current databases. Additionally, testing for true ileal protein digestibility will allow the tool to calculate Digestible Indispensable Amino Acid Score. It will also be important to determine which ingredients or ingredient combinations improve acceptability and palatability of RUF in local contexts. Moreover, production cost needs to be reflected in the choice between RUF formula alternatives that require a different manufacturing process.

Development of a micronutrient premix, acceptability testing, and—as required for RUTF—subsequent efficacy trials will serve to validate LP results and further modify and improve nutritional constraints. Based on acceptability and efficacy trials, recipes of proven alternative cost-effective RUF formulae can be developed to facilitate local choices and production.

The use of my LP tool can support RUF formulae optimization to reduce RUF ingredient cost (including the replacement of costly dairy ingredients), enable local production, reduce contamination risk, and cut environmental footprint (viz., crop water footprint and transport carbon footprint), thus allowing improved malnutrition treatment efforts.

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CONFLICTS OF INTEREST

The authors declare that they have no conflicts of interest.

CONTRIBUTIONS

GB is the sole author. No contributions have been received other than those listed in Acknowledgements.

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