Breads from African Climate-Resilient Crops for Improving Diets and Food Security

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Preface

Global challenges ...
Africa's rapid population growth and massive urbanization creates significant challenges to the food system in feeding all these people, while at the same time facing the negative effects of climate change and disruptions in (global) food supply chains. Furthermore, urbanization causes replacement of traditional meals based on locally produced crops with convenience products with lower nutritional value which negatively impacts nutrition security in sub-Sahara Africa. However, these local crops are underutilized, while Africa increasingly depends on imported wheat for food. The ever-growing dependency on imported food results in lost opportunities for economic activities along the African food production chain and makes the African food system very vulnerable to disturbances, like the current wheat crisis making wheat products unaffordable for low-income consumers.

Figure 1 Peter Arinaitwe, chapati-maker in the Kasanvu Slum in Kampala, Uganda, in his street stall baking a chapati based on local climate-resilient crops instead of imported wheat.

... affecting people's daily lives in Sub-Saharan Africa
Peter Arinaitwe is chapati-maker in the Kasanvu Slum in Kampala, Uganda. His wheat flour chapatis with some beans (Kikomando) are a popular meal and important part of the daily diet. In his street stall Peter can make his chapatis with very limited tools and hence provide affordable foods on the go for low-income urban consumers. The prices of wheat and fuel are increasing rapidly, but Peter can't raise the prices as his low income clients can't afford it. Peter is forced to make the size of his chapatis smaller and smaller, leaving the stomachs of his clients more and more unfilled.

This white paper aims to provide some practical guidance and examples for local stakeholders and entrepreneurs to make attractive, nutritious bread products based on Climate-Resilient Crops. Part of the information in the white paper is the result of the recently completed NUTRIFOODS project coordinated by Wageningen Food & Biobased Research. The project included several EU and African partners and aimed to promote the use of climate-resilient African crops into nutritious bread products and hence reduce Africa's dependency on imported wheat.

More information about the NUTRIFOODS project, partners and research outputs can be found at:

www.wur.eu/nutrifoods

Summary

In Africa, rural communities traditionally prepare meals from locally grown crops like cassava, sorghum and pulses, which are considered Climate Resilient Crops (CRC). However, with fast population growth, urbanization, and increasing disposable incomes, consumption of foods based on refined cereals, like breads made from mostly imported wheat, is increasing rapidly and replacing traditional meals. Over time, Africa has shifted from being a net food exporter to being a net food importer. This growing dependency of Africa to imported foods is a huge economic problem and makes the African food system highly vulnerable for disruptions like COVID-19 and the wheat and fuel crises due to the Ukraine war.

Promoting the use of CRCs into nutritious bread products can reduce Africa's dependency on imported wheat by developing value-adding processes that create new economic activities along the African food supply chain and increase the demand for CRCs. A systematic analysis of the challenges and opportunities for the CRCs at food system level and the identified consumer and market needs for CRC-based bread products, indicated that a substantial increase in the cultivation and consumption of CRCs would lead to considerable nutritional, economical and sustainability improvements in the sub-Sahara African food system and increase its resilience.

CRCs have in common that they lack technologic functionalities and properties to effectively compete with wheat flour, although their nutritional value is comparable to or better than wheat flour. However, various processing technologies to improve CRCs can be implemented which are simple and cost-effective. In particular dry heating, roasting and extrusion are promising. Most of all, blending of CRCs proved to offer broader opportunities compared to single crops for wheat replacement. For instance, a highly versatile mixture of sorghum, cowpea and cassava was developed and successfully demonstrated in the local situation at street vendors in Uganda to provide highly attractive and satiating chapatis for low-income consumers. Also CRCs-based tin breads in African bakeries gave promising first consumer responses. These CRCs-based breads were also adapted for the gluten-free market in EU, produced in a Dutch industrial bakery and tested with consumers to provide export opportunities for African ingredients.

This white paper provides practical guidance for local stakeholders and entrepreneurs to make attractive, nutritious bread products based on Climate Resilient Crops.

In the short term, mixtures of CRCs can provide an alternative to wheat and hence provide affordable, nutritious food to low-income consumers. Current implementation and commercialization of these results in Uganda focuses on setting up supply chains and development of consumer products. Short term implementation in other countries is highly feasible by formal as well as informal businesses.

Also in the long term, it is important to reduce Africa's dependency on imported food by improving CRCs availability as functional ingredients and by increasing their use in value-added food production. This can clearly provide nutritional, economical and sustainability improvements and contribute to a more resilient food system.

1 The food and nutrition security issue in SSA through a food system lens

For a vast majority of people in Sub-Saharan Africa (SSA), especially those living in rapidly growing cities, access to enough, good quality, and constant supply of food remains an obstacle to good nutritional health. This situation has been further exacerbated by the current global food crisis, with supply chains disrupted by the pandemic and international conflicts, climate change causing more frequent and severe natural hazards, and with food prices reaching historic highs and becoming more volatile. In this context, the dependency of SSA on imported wheat is no longer sustainable in the short-term with food insecurity rising dramatically. However, radical transformations in the SSA food system are challenging due to the complex, multifaceted and non-linear processes involved and by the possible trade-offs between interventions and objectives. In a food system approach a holistic view on the production system, socio-economic and environmental drivers and outcomes (food supply, nutrition and economic benefits) is used. This provides a useful conceptual framework to evaluate the sustainability and effectiveness of potential interventions[1] (Figure 2).

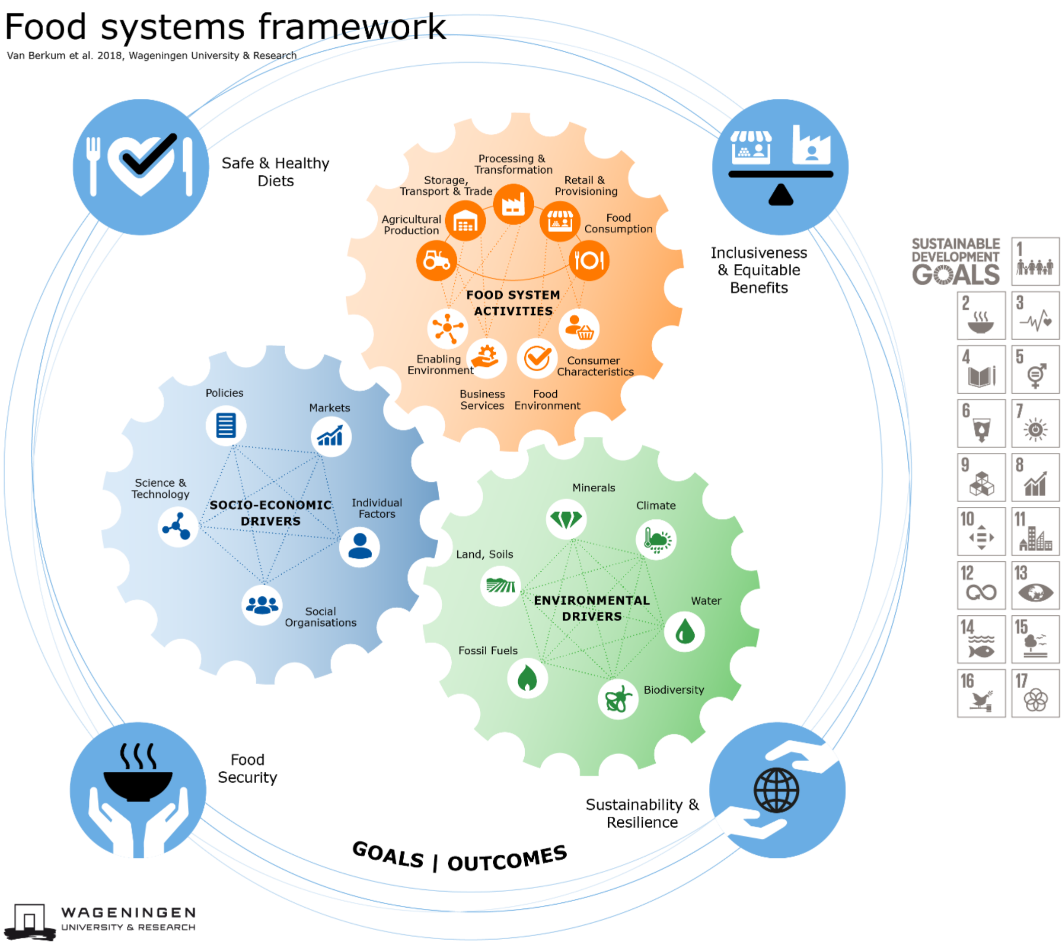


Figure 2 The food system can be seen as all activities of the agricultural and food production as well as their socio-economic and environmental drivers. All these elements influence each other and together they lead to the level of food (in)security, availability of safe and healthy diets, fair distribution of costs and benefits, and sustainability and resilience of the system to coop with disruptions like for instance the wheat crisis or climate changes[2].

[1] www.wur.eu/foodsystems
[2] van Berkum, S.; Dengerink, J. and Ruben, R. 2018. The food systems approach: sustainable solutions for a sufficient supply of healthy food. Wageningen, Wageningen Economic Research, Memorandum 2018-064. https://doi.org/10.18174/451505

The food system approach was adopted to evaluate whether the valorization of Climate-Resilient Crops (CRCs) into convenient bread-type products could reverse the trend towards increasingly using (imported) wheat as main staple and foster sustainable, sufficient and healthy diets[3]. The systematic analysis of the benefits, opportunities, bottlenecks and possible drawbacks or trade-offs provided key outcomes that need to be taken into account for practical implementation of technological solutions in bread product applications.

From a nutritional perspective, flours from CRCs are more valuable ingredients than refined wheat. Their use is hindered by lack of the required technological properties and of knowledge to improve their functionality in bread applications. Therefore, CRC flours cannot be easily processed into the convenient wheat-based bread-type products which have attracted SSA consumers. Simple and cost effective technological solutions are therefore needed to address these food processing challenges. Considering the complexity of the fragmented consumer market with strongly diversified consumer segments as well as the huge range of local products, generic technological solutions are preferred which enable the development of attractive and convenient food products which can be adapted to the needs and demands of the local market.

When these challenges are addressed, they could provide a substantial trigger to develop supply chains for value-added CRCs ingredients and to invest in CRCs-specific agriculture to improve yields and productivity. In turn, these developments would attract more farmers and thereby increase CRCs' availability. These actions should be further supported by raising consumers awareness of the cultural, environmental, nutritional and economic benefits of CRCs and by adopting economic incentives and policies involving multiple stakeholders.

This white paper discusses in further detail CRCs, consumers and markets in SSA, nutritional and technological aspects of CRCs, and approaches for developing attractive, versatile and convenient bread-type products, and presents practical case studies of products for local implementation.

[3] Noort, M.W.J.; Renzetti, S.; Linderhof, V.; du Rand, G.E.; Marx-Pienaar, N.J.M.M.; de Kock, H.L.; Magano, N.; Taylor, J.R.N. 2022. Towards Sustainable Shifts to Healthy Diets and Food Security in Sub-Saharan Africa with Climate-Resilient Crops in Bread-Type Products: A Food System Analysis. Foods 2022, 11, 135. https://doi.org/10.3390/foods11020135

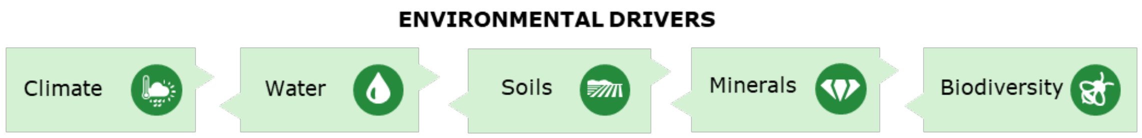
2 Climate-resilient crops in a more resilient food system

The world's food production is highly dependent on three dominant commodity grains - wheat, maize and rice – in refined form, which together account for 50-60% of the global protein and calorie intake. Whereas the climate change will even allow increased agricultural productivity in region with moderate climates[4], the tropical and arid regions of SSA are facing large disadvantages[4]. In SSA, climate change is predicted to reduce the productivity of wheat, maize and common beans by 18–35% by 2050[4]. In turn, this is expected to substantially compromise food security and increase Africa's dependency on imported food. Either way, the poorest and the vulnerable segments of the population will be most severely affected.

Food crops can be regarded to be climate-resilient if their cultivation is resilient to the abiotic stresses like drought, heat and flooding that are becoming more frequent as a result of climate change. Climate-resilient crops of interest for SSA include a wide variety of starch-rich crops: cereals (e.g., sorghum, fonio, teff and finger millet), pseudo-cereals (amaranth), roots and tubers (cassava and sweet potato), pulses (Phaseolus beans, cowpeas, chickpeas, pigeon peas and Bambara groundnuts) and oilseed legumes (soy beans and peanuts). All these crops are grown across SSA, obviously depending on the local conditions, and many are indigenous. Major food crops like cassava and Phaseolus beans originated in the Americas and alike maize were later introduced to Africa.

In SSA, CRCs are expected to sustain their productivity on average or even show some increase in productivity in face of the predicted climate changes[4]. In most cases, less water is needed for their cultivation. Additionally, some of these crops, e.g. sorghum, have deeper rooting which allow them to grow on more marginal land and prevent soil degradation. On the other hand, pulses like cowpea grow in low rainfall and shade and have the capability to fix atmospheric nitrogen and thus reduce fertilizer dependency. For such reasons, these crops are suitable for intercropping, reducing soil erosion, and improving cereal yields. Additionally, diversification in agricultural practices and heterogeneity in crops enhances ecological resilience and biodiversity. Overall, promoting CRC production and use in food applications has the potential to improve food and nutrition security and to improve the sustainability and resilience of the food system in SSA.

Increasing the production and use of CRCs will contribute to food security in the face of climate change, while using less resources, since they are adopted to the African climate and conditions. Cultivation of these crops in heterogeneous systems -and more particular pulse-cereal combinations- can provide several environmental advantages like reduced fertilization, improved soil and biodiversity.



To date, several factors undermined a more widespread use of CRCs in food products. Most technological and scientific developments for improving crop productivity (i.e. breeding) and agronomical practices (i.e. fertilizers, pesticides, etc.) have primarily focused on the major staple crops, such as wheat, rice, maize, soy beans and to a lesser extent or not at all to CRCs. This unbalanced development - hence the often used term

[4] Barros, V.R.; Field, C.B.; Dokken, D.J.; Mastrandrea, M.D.; Mach, K.J.; Bilir, T.E.; Chatterjee, M.; Yuka, K.L.E.; Estrada, O.; Genova, R.C.; et al. Climate Change 2014 Impacts, Adaptation, and Vulnerability Part B: Regional Aspects Working Group II Contribution to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change; Cambridge University Press: Cambridge, UK, 2014

‘neglected crops’ - has contributed to a shift in production from indigenous and traditional crops to the global commodity crops. In the case of SSA, this resulted in a very large increase in cultivation of maize and cassava. The gap in productivity of CRCs compared to wheat and the availability of wheat at competitive prices has marginalized CRCs cultivation as main commodity and limited their production to restricted agronomic conditions (e.g., arid conditions, poor soils).

The underdevelopment for CRCs is not limited only to primary production. Throughout the food supply chain, the global commodity crops like wheat have catalyzed the attention towards scientific and technological developments, scale and uniformity in terms of processes and product applications. In turn, the availability of CRCs in the market is not reliable, hampering food producers and businesses to develop economic activities using these crops, thus creating a vicious downward spiral for their use and value. Creating market demand for CRCs based on offering attractive new CRCs-based products to consumers has the potential to invert current trends.

3 Economic potential and food affordability

Agricultural production is one of Africa's most important economic sectors. Production and export of crops is of ample economic importance, but also the domestic market is large, with African consumers spending on average over half of their income on food. However, agricultural productivity in Africa could not keep pace with the increasing demand due to population growth, resulting in Africa shifting from a net agricultural exporter to a net agricultural importer. The dependence of Africa on imported wheat continues to increase with, for example, Kenya and Uganda importing 68% and 95%, respectively, of their domestic needs. The increasing import of wheat negatively affects the SSA economies due to the cost in foreign exchange and -maybe even more important- the fact that it constrains the development of local agri-food value chains and economic activities.

Since locally produced crops can't compete with the imported wheat based on economic and functional aspects, a vicious cycle drives the food system to more import-dependence at the expense of locally produced crops. Currently, CRC-based food value chains remain predominately traditional and short, with farmers often selling their produce directly to end consumers or small-scale traders and processors. Therefore, these crops currently provide very limited value-added processing activities and consequent economic benefits to local communities, and contribute little to food and nutrition security in rapidly growing cities. The lack of value-adding activities based on local produce is a missed opportunity, as it is a known pathway for economic growth and generating jobs. However, by comparing the composition of jobs in different activities in the food chain among different economies, it is clear that creating value-adding processes and services for the local produce could generate economic activities and jobs in African economies and contribute to economic development (Figure 3).

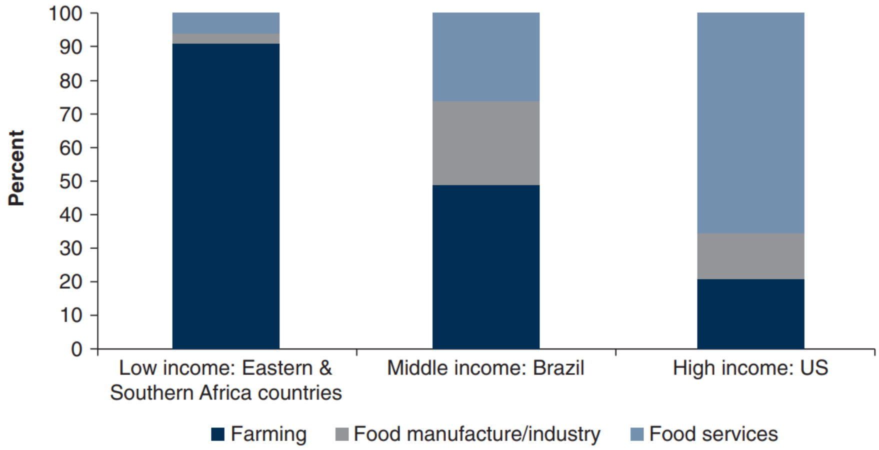


Figure 3 Composition of jobs in the food system in low-, middle-, and high-income countries[5].

A critical point is how to break these vicious cycles and contribute to a more resilient African food system. Flourishing CRCs food value chains, based on value-adding processing of local produced crops, will not only provide employment and income, but also increase demand for local crops, hence contributing to the local communities' ability to secure their primary food demands and increase their disposable incomes. Using the food market as the key-incentives to stimulate CRCs use and uptake and build economic activities, CRCs food products need to be attractive and convenient for urban consumers from low to middle incomes as these market segments are most evolving and provide many opportunities for value-adding processes as well as services[6]. SMEs in food processing and supply in formal and informal urban food systems offer the largest economic growth potential (the power of the middle) needed to drive innovation and scaling of supply chains.

[5] Tefft et al. (2017). Food Systems for an Urbanizing World, The World Bank and Food and Agriculture Organization of the United Nations. Knowledge Product.

[6] Reardon, T., Liverpool-Tasie, L.S. O., and Minten, B. (2021). Quiet Revolution by SMEs in the midstream of value chains in developing regions: wholesale markets, wholesalers, logistics, and processing. Food Security. https://doi.org/10.1007/s12571-021-01224-1

For SME's and street vendors to adopt local crops in their products - besides the fit for use - the price of the ingredients is essential. With the usually lower prices of imported wheat, local crops can't compete on price, which is an important hurdle limiting their use. However, due to the current higher and more volatile wheat prices CRCs competitiveness has improved. It is very important to evaluate the economic viability of new CRC based foods during product development stages. Cost calculations indicate that currently a mix of local crops in Uganda can replace wheat on a cost neutral basis or can even reduce costs, which can drive short term uptake of local crops by food entrepreneurs (see in Case 1, page 22). Economic aspects are essential to secure SME profitability and incentivize commercial activities while also ensuring food affordability for the consumers in the base of the pyramid. However, it is important to stress that prices of food materials vary largely between countries, regions and in time, and price compatibility remains an important bottleneck for local crops.

Increasing the production and use of CRCs will have many socio-economic benefits for African countries, generate economic activities to provide jobs and income along the food supply chain. With the current high wheat price, a clear improvement of food affordability can be achieved.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4 Consumer and market

The African population is relatively young and the majority of the consumers have a low- to middle-income. The market can be characterized as largely informal with mainly smallholders, street vendors, small proprietors, and some SMEs. The majority of the African population depends on the informal food market for affordable, available food provision and nutrition security[7]. Due to the rapid urbanization, the informal urban market for the low- and middle-income consumers is rapidly evolving. This market should be a main focus of the attention for the development of CRCs-based products.

The major trends for bread-type products within low- and middle-income consumers are largely driven by affordability, convenience, Westernization and health awareness[2]. Especially at the lower end of the market, **affordability** of food will at times override all other preferences. However, it is important to note that economically deprived consumers are quality-conscious when buying food, since they allocate a much larger proportion of their disposable income to food compared to more affluent consumers. Hence, poor consumers are highly concerned about food quality and value as far as they can afford it. **Convenience** is an important trend across (urban) population segments as most consumers have busy lifestyles with little time to spend on food purchasing, cooking and eating. Particularly in urban settings, convenience aspects of food that influence food choice include the ease of availability (e.g. street vendors near working places), the possibility for consumption on-the-go, availability of ready-to-eat products, and their versatility (i.e. to be consumed on its own or combined with other meal components). Younger consumers in many African countries aspire to consume **Westernized** food products, promoted through marketing and social media. For foods based on local crops, this trend can be a huge pitfall, since products based on traditional grains and pulses are easily viewed as "the antithesis of cool". Traditional food crops and their products are also often refer to as "poor man's" food. Consumers globally are becoming more aware of the impact of food choices on **health**, especially amongst higher-income, more educated consumer groups. However, in particular lower-income consumers lack education and health-awareness or may associate health with other food elements, such as colour or size.

A Rapid Market Appraisal was conducted in Uganda, Kenya and South-Africa in 2020 as part of the NUTRIFOODS project. The results indicated that low-income African consumers and value chain actors were hardly aware of the possible health and economic benefits of wheat-reduced or CRCs-based bread products. This suggests that among this population segment benefits in price compared to current wheat-based products are required, unless awareness and knowledge is raised significantly. In contrast, higher-income consumers place a large emphasis on sensory and quality characteristics of CRCs-based products and their nutritional properties. Currently, the global food and wheat crisis have significantly increased consumer awareness and interest in alternatives for imported wheat. The price of imported wheat contributes to more favorable economic potential of using local crops and the local businesses in bread-type products are already reacting by diluting wheat with alternative crops which are locally available[8].

The current global food and wheat crisis and the compelling economic aspects favors the introduction in the market of bread-type products based on CRCs. Sustained consumption of these products across different consumers segments in the longer term relies on their affordability, convenience, versatility, taste and nutritional benefits.

[7] Reardon, T., Liverpool-Tasie, L. & Minten, B. Quiet Revolution by SMEs in the midstream of value chains in developing regions: wholesale markets, wholesalers, logistics, and processing. Food Sec. 13, 1577–1594 (2021). https://doi.org/10.1007/s12571-021-01224-1

[8] www.bbc.com/news/av/world-africa-63235963

5 Nutritional properties of CRCs

The nutritional properties of relevant CRCs from cereals, pulses and tubers or roots are distinguished from the major crops wheat and maize can, as exemplified in Table 11. Cereals like sorghum, wheat and maize grains typically contain 70-75% starch, depending on cultivar. The protein content is on average 7-13%. In pulses, like cowpeas, the starch content is generally lower ranging from 30 to 65%. On the contrary, the protein content is substantially higher than in cereals, typically ranging between 17 and 35%. Tubers and roots are by far the highest in starch content, up to 83-86%, and therefore a good source of energy while their protein contents are the lowest. The dietary fiber content can vary substantially depending on the processing conditions for deriving a flour from the original raw material. In cereals and pulses, fibers are mainly distributed in the outer layers of the grains, i.e. the bran and seedcoat respectively. From this standpoint, processing CRCs as wholegrain contributes to a more balanced nutritional composition compared to the refined wheat and maize grains that are currently used as dominant commodities in SSA.

Table 1 Nutritional composition of CRCs compared to wheat and maize flour.

	Refined wheat flour	Degermed maize flour	Sorghum whole flour	Cassava meal	Cowpeas whole
Energy (kJ/100g)	1510	1512	1377	1455	1406
Moisture (g/100g)	13.4	12	12.4	12	12
Protein (g/100g)	11.98	8	10.2*	2.96	23.9*
- Lysine (g/100g)	0.231	No data	0.229	0.096	1.591
Carbohydrates (g/100g)	72.5	78	73.1*	83	40.7*
- Sugars (g/100g)	0.31	0	2.53	3.71	6.9
- Dietary fiber (g/100g)	2.4	2	10.5*	3.92	20.6*
Lipids (g/100g)	1.66	2	3.46	0.61	1.26
Folate (µg/100g)	33	No data	20	59	633
Calcium (mg/100g)	15	0	13	35	110
Iron (mg/100g)	0.9	0	3.36	0.59	8.27
Zinc (mg/100g)	0.85	No data	1.67	0.74	3.37

*Nikinmaa et al., 2022[9], all other data from Noort et al., 2022[3].

Among CRC cereals, sorghum is particularly of interest for its nutritional properties. Due to its unique grain structure, a proportion of the starch in sorghum can act as resistant starch (i.e. dietary fiber). For this reason, incorporation of sorghum in staple foods may be beneficial towards disorders such as diabetes and obesity. Additionally, phytochemical compounds present in sorghum like tannins can further reduce starch digestion, resulting in a low glycemic index. The array of anti-oxidant compounds in sorghum, mainly phenolics, are not commonly found in other cereals, and are reported to provide unique anti-inflammatory activity. Sorghum is also an important source of minerals, particularly rich in potassium and phosphorus and with good levels of calcium. Iron, zinc and manganese are present in minor amounts. Sorghum is an important source of fat-soluble and B-complex vitamins, except vitamin B_{12}. These micro-nutrients are mainly located in the outer layers of the grain and in the germ. Therefore, consumption of whole grain sorghum is recommended as opposed to refined sorghum products.

[9] Nikinmaa, M.; Renzetti, S.; Juvonen, R.; Rosa-Sibakov, N.; Noort, M.; Nordlund, E. Effect of Bioprocessing on Techno-Functional Properties of Climate-Resilient African Crops, Sorghum and Cowpea. Foods 2022, 11, 3049. https://doi.org/10.3390/foods11193049

Protein quality of cereals is generally low due to the limited amounts of the essential amino acid lysine (Table 1). Cowpea is considered to be one of the main high-quality plant protein sources in the tropics. Aside for being a rich source of proteins, cowpea proteins are rich in glutamic acid, aspartic acid, and lysine which are limited in sorghum. Additionally, cowpea is a valuable source of vitamins such as folate and of minerals such as iron and zinc. For these reasons, it is nutritionally beneficial to complement CRC cereals and tubers such as sorghum and cassava with legumes like cowpeas. Cowpea also contains a remarkable amount of resistant starch and dietary fibers, thus reducing the amount of blood glucose and making cowpea a low glycemic food.

It should be noted that in cereals and legumes, minerals' bioavailability is negatively related to the proportion which exists bound as phytates. From this perspective, phytate is considered the major antinutrient as it chelates essential divalent minerals such as iron, zinc and calcium. In cereals, phytate is largely concentrated in the outer layers and consequently its contents are largely reduced in refined flours. This is not the case in legumes such as cowpea, as phytates are largely present in the inner part of the grain. However, traditional processing methods commonly implemented to produce food from grains (e.g. fermentation, roasting/dry-heating, cooking) are generally recognized to reduce the contents of these anti-nutritional factors. Therefore, simple and cost-effective technological interventions are important to provide CRC flours with added value in both technological and nutritional functionality.

Substituting refined wheat flour with blends of CRC flours like sorghum, cowpea and cassava into convenient staple food like bread can promote a substantial improvement in the nutritional quality of the diet in SSA.

6 Functional properties of CRCs

Refined wheat flour started to become a valuable commodity when wheat bread and bread-type products were introduced in Africa during the colonial era, as their soft and aerated texture became increasingly popular among local consumers. These textural characteristics are due to the ability of refined wheat flour (i.e. gluten) to provide a workable, visco-elastic dough when hydrated and kneaded and to retain gas bubbles. Due to the lack of gluten, CRC flours do not possess the same functionality as wheat. This is a major technical reason for the increasing underutilization of CRCs. Most imported wheat is produced very efficiently and allows the production of a wide variety of modern and convenient western food items like breads, chapattis, biscuits, baked products and snacks. In contrast, CRCs are mainly used for making traditional foods like pancake-type flatbreads (e.g. Injera), couscous, porridges, mashes and pastes (e.g. Fufu and Ugali).

Traditionally, CRCs have long been subjected to processing practices in order to improve their functionality, also for traditional bread-type applications such as Injera. A common practice has been the use of pre-cooked CRC flours in combination with native flours in order to thicken the dough and hold some of the gasses produced during fermentation. Often, the flour-water mixture is subjected to a mixed lactic acid bacteria and yeast fermentation. However, traditional fermentation practices are often labour-intensive and time-consuming as they generally take some days.

The traditional processing practices have also been used for nutritional and safety purposes, aside from the technological implications. For instance, lactic fermentation in sorghum flour improves protein and carbohydrate digestibility. Fermentation also increases contents of B vitamins. Furthermore, it is effective in degrading phytic acid and consequently increasing the mineral availability. The reduction of pH to 4 as obtained by common lactic acid bacteria fermentations also inhibits the growth of pathogenic bacteria.

In order to promote CRCs as value added ingredients, it is critical to revisit traditional practices to improve functionality, nutritional and safety aspects while limiting additional processing costs and complexity. Traditional practices are also increasingly of interest among consumers who are challenging food industry towards a reduced use of additives and unfamiliar ingredients. From these perspectives, minimal processing technologies provide opportunities to reduce the amount of ingredients that are unfamiliar to the average consumer. Nowadays, traditional technologies such as sprouting/malting, dry-heating, roasting and fermentation techniques have gained attention for enhancing the functionality of cereal and legume flours.

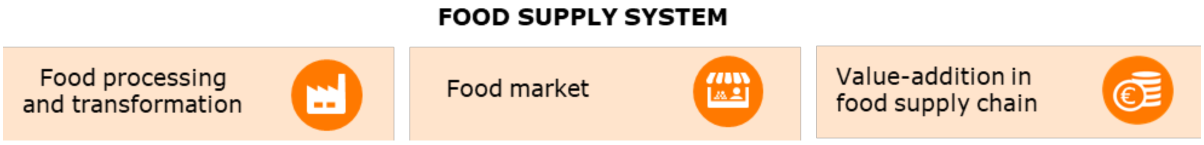
Dry-heating of CRCs is of particular interest since improvements in techno-functional properties may be combined with sanitization of low moisture food. Dry-heating is safe, simple and requires little cost, time and no use of chemicals. It is an interesting technique to improve the functionality of flours by physical modification. For CRCs, dry-heating of legume flours such as cowpea has been applied by careful selection of temperature conditions for treatments combined with (low) moisture contents of the flour[10]. As a result, the functionality of the cowpea flour could be selectively modulated, thus providing opportunities to improve its technological performance depending on the requirement of the specific end-product application. For bread-type applications such as tin breads, the dry-heated cowpea showed the ability to improve bread quality by increasing volume and softening the bread crumb. An additional benefit of dry-heating is its ability to modulate flavour, especially for reducing the beany flavour of legumes, and to inactivate antinutritional factors, e.g. phytate. Overall, dry-heating can improve both functionality and microbial safety in low moisture food such as flours. This simple and cost-effective technique can be easily adapted to other cereals and legumes and offers the opportunity for value-addition to diverse CRCs.

[10]Renzetti, S.; Heetesonne, I.; Ngadze, R.T.; Linnemann, A.R. Dry Heating of Cowpea Flour below Biopolymer Melting Temperatures Improves the Physical Properties of Bread Made from Climate-Resilient Crops. Foods 2022, 11. https://doi.org/10.3390/foods11111554

Fermentation technologies also have the potential to provide specific modifications to CRCs, and can be implemented in current food processes. For CRCs, fermentation seems most suitable for legume flours as a means to improve flavour and reduce antinutritional factors. In flours such as sorghum, fermentation proved challenging for improving technological functionality[8]. However, fermentation of CRC flours with selected bacterial strains can be an effective means of biofortification of CRC-based staple foods to address vitamin B_{12} deficiency resulting from limited consumption of animal-derived food[11] and to improve protein digestibility.

The most simple and cost effective approach to functionalize CRC flours is to optimally blend them into a functional mixture. A flour blending approach was developed and implemented to fully replace wheat flour by a mixture of sorghum, cowpea and cassava[10,12]. In this approach, water binding and pasting properties of the flour mixture were optimally balanced for tin breads and flat breads applications, providing doughs which could be processed either by hand or with bakery equipment of both traditional and industrial bakeries. Psyllium flour was added in small amounts to obtain a workable dough after hydration and mixing. Additionally, mixing sorghum, cowpea and cassava allows to modulate the flavour and aroma profile of breads and to optimize towards taste preferences[13]. Overall, optimal blending of CRCs proves to be a very versatile approach which can be adapted depending on local requirements in terms of taste and available flour sources, as further detailed in the next section.

The functionality of Climate-Resilient Crops can be enhanced by low-cost technologies such as dry-heating, roasting, extrusion and fermentation to provide value-added, safe ingredients for food production. Additionally, CRC flour blending is a simple and cost effective approach to enhance the use of CRCs in place of wheat. Value-adding activities on CRCs offer new commercial opportunities, and hence can create jobs and employment along the food supply chain.



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7 CRCs-based bread-type products

Among CRCs, sorghum and cassava have been widely studied for partial wheat replacement in bread-type products. Since both flours lack the functionality of wheat gluten, their inclusion has a detrimental effect on the final product, particularly for inclusions of 15% and beyond. For sorghum-wheat composite breads a maximum inclusion of 30% sorghum was found acceptable in tin bread by consumers'[14].Despite the many programs dedicated to valorization of cassava in wheat bread applications, widespread implementation in commercial products has failed to date, also due to technological challenges and poor product quality of cassava-wheat composite breads as perceived by consumers and local bakers. To date, the paradox in the composite breads interventions was that policies were developed not to primarily meet the needs and preferences of the consumer, but rather the interests of those further up the supply chain, in particular smallholder farmers as well as to increase the country's balance of trade by importing less wheat flour[15]. In contrast, innovations that create new markets for CRCs are critical to promote their primary production and transformation into convenient food and consequently economic activities for their entire value-chain. From this perspective, bread-type products entirely based on CRCs could foster the implementation of new value chains towards innovative products with their own characteristic qualities.

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In contrast to the partial wheat replacement, bread-type products made entirely from CRCs have not received much attention. Combinations of CRCs flours such as sorghum, cassava and cowpea offer opportunities to optimize nutritional profile and technological properties towards applications in bread-type products[11]. These concepts would benefit both African consumers as well as those with gluten-related intolerances as these flours are naturally gluten-free. Since the quality of CRCs-based bread products is not dependent on the unique functionality of gluten, working with mixtures of CRCs provides more freedom to formulate and adapt the product concept to nutritional and consumers' requirements of the local situation.

From a market and consumers' perspective, CRCs based type-breads can be proposed to consumers as new products with their own characteristic quality. For tin bread applications, an important advantage is that CRCs mixtures do not necessarily need to meet expectations of exact volume and shape of wheat breads, which has been a major pitfall for composite wheat breads with regards to consumers' expectations. The main important features are that the CRCs-based dough are processable, can be adapted to different product applications (e.g. from flatbreads to tin-breads to fried dough) and result in tasty, nutritious and convenient products which are accepted by local consumers.

A mixture of sorghum, cassava and cowpea has been for the first time proposed by Wageningen researchers to produce a dough that was processable similarly to a wheat dough[10,12]. This concept dough can be adapted with regards to the ratio of e.g. sorghum and cowpea in order to optimize the nutritional profile, the taste and the textural properties of the breads[12]. At laboratory scale, this formulation concept showed to be adaptable to diverse product applications such as in yeast-leavened products like tin breads as well as in unleavened products like flatbreads. The adaptability of this product concept to the situation in Sub-Saharan Africa has been recently tested in Uganda. Street vendors were provided with a ready-to-use flour mixture to produce chapatti whereas local bakeries produced tin breads. In both cases, sorghum, cowpea and cassava from different sources were used. Overall, products could be produced without major technological issues and good bread-type products could be produced also from different sources of flours, thus proving that these CRC-based dough formulations are versatile and can be successfully adapted to the local situation. Additionally, adaptations of the basic formulation concept were performed to provide a gluten-free bread for the European market. These three different products are described in the following case studies sections.

Valorization of flour mixtures made from sorghum, cowpea and cassava in bread-type products offers a unique opportunity to support food and nutrition security in SSA by exploiting synergies in technological functionality, nutritional properties and agricultural practices.

Case 1. CRCs-based Chapatti as street food in SSA

Chapatti is a very popular unleavened flatbread in East-Africa, in particular for low-income consumers. A processable dough for chapatti can be prepared very easily by hand based on a pre-mix of local crops as shown in Table 2 Basic formulation for 2kg CRC chapatti flour mix. This pre-mix of local crops and some psyllium flour can be used as a full replacement of wheat flour usually used by the street vendors. This basic formulation can be adjusted in view of local crop properties, towards local taste and texture preferences (see case 2), or for instance to improve the cost effectiveness (see Table 4).

Table 2 Basic formulation for 2kg CRC chapatti flour mix.

Sorghum flour	851	gram
Cassava flour	851	gram
Cowpea flour	162	gram
Psyllium flour	136	gram

Table 3 Basic recipe for CRC chapattis.

CRC chapati flour mix	500	gram
Salt	10	gram
Sugar	17	gram
Water	489	gram
Vegetable oil:	add a bit to dough and for frying	

This pre-mix of local flours and basic recipe in

Table 3 were successfully tested with a chapatti-maker in Kasanvu Slum (Kampala, Uganda) based on the chapatti-maker's skills and the utensils available in his stall. The CRCs-based dough can be easily prepared in a bowl, and needs very limited manual mixing, as no gluten-network has to be developed. The dough can be shaped into small dough balls (about 90 g for a large 500 UGX chapatti) as typically performed by the vendors (Figure 4A,B). After some resting time, the dough pieces are first flattened by hand with some CRC flour to avoid sticking and thickness can be further reduced with the help of a small roller (Figure 4C).

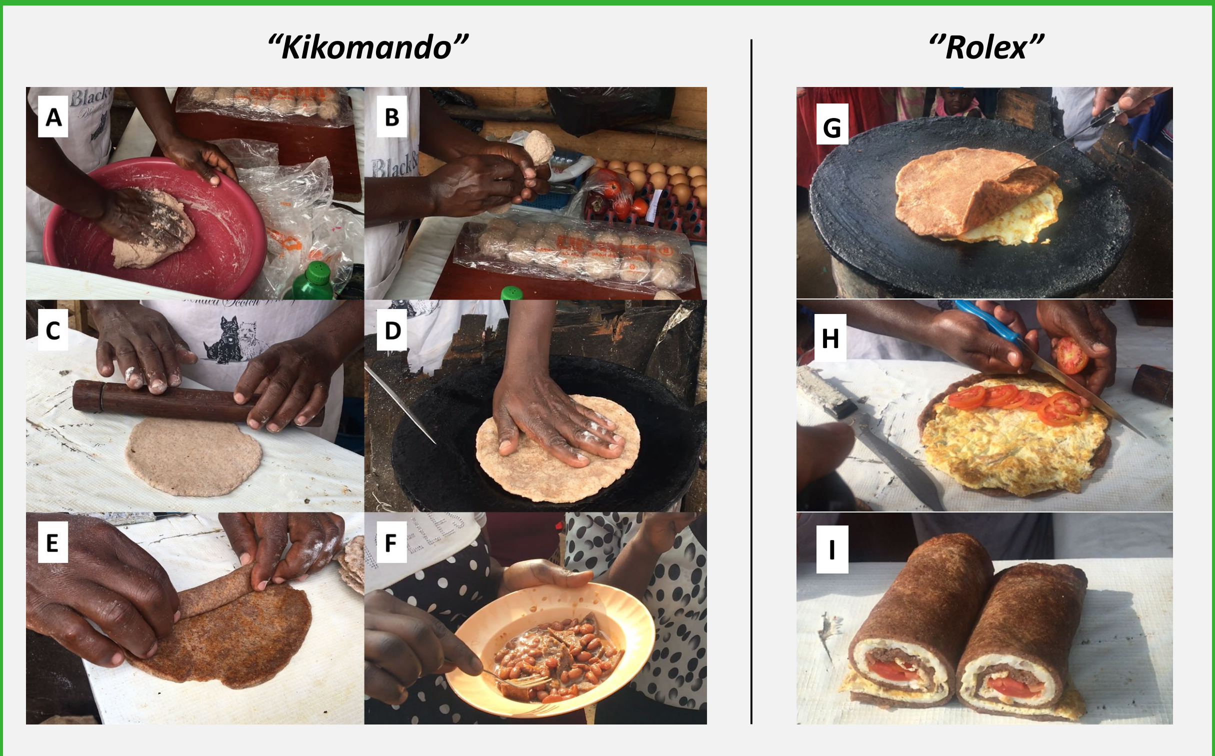

Figure 4 Main steps in the preparation of chapatti by a street vendor using the CRCs-based dough to serve popular dishes like Kikomando (chapatti with beans) and Rolex (chapatti with fried eggs and vegetables), figure adapted from Renzetti et al. 2022[12].

The CRCs-based chapatti can be baked on an open-fire heated pan with oil, while manually pressing back the puffing dough during the short baking time (Figure 4D), and sold as such. Alternatively, it can be easily rolled up (Figure 4E) and cut in pieces and served as Kikomando (i.e. chapatti with beans, Figure 4F). The chapatti can be also baked together with eggs (Figure 4G), then rolled with fillings like sliced tomatoes (Figure 4H) to be served as Rolex (i.e. chapati rolled-eggs Figure 4I).

These chapatti have a mild, pleasant taste and similar texture to normal wheat-based chapatti and can also be rolled similarly. During the tests in Uganda, both vendors and their local customers showed to appreciate the CRCs-based products.

Since the combination of several CRC flours in the pre-mix should be balanced for e.g. their functional properties, the full recipe is too complex and a pre-mix of ingredients that can be used as single flour needs to be provided by for instance a local SME. In the case of Kampala, Uganda, currently the not-for-profit organization Bake for Life foundation is setting-up a local supply chain. A local business will buy and mix the CRC flours in 2 Kg bags of pre-mix to be sold to street vendors. It is envisaged to setting up a distribution system through some early adaptors re-selling it to other street vendors.

For SMEs and street vendors to adopt local crops in their products -besides the fit for use- the cost efficiency of the ingredients is essential. The economic viability of chapatis based on local crops has been evaluated by cost calculations made by commercial partners in Uganda, and are shown in Table 4. The cost calculations indicate that the mix of local crops can replace wheat on a cost neutral basis with the current high wheat price. Already some tests were performed to further reduce the ingredient costs, by reducing the amount of psyllium flour, which is the most expensive functional ingredient in the mix. By re-balancing the CRCs in the mix, i.e. increasing the cowpea content, the psyllium could already be reduced substantially as shown in the last columns of Table 4. In this way the product quality could be maintained, while substantially improving the margin, and provide an important economic incentive to switch from wheat flour to local flours. It is very important to note though, that prices of food materials vary largely between countries, regions and in time, and the setting-up of value and supply chains requires attention.

Table 4 Cost calculation for chapatis made by street vendors in Uganda.

	Wheat based chapati		**Local crop chapati**		**Local crop chapati reduced psyllium**	
	kg	UGX	kg	UGX	kg	UGX
Wheat flour (3,200/kg)	0.621	1988	0.000	0	0.000	0
Sorghum flour (2,500/kg)			0.209	524	0.210	526
Cassava meal (1,800/kg)			0.209	377	0.191	343
Cowpeas flour (2,000/kg)			0.040	80	0.076	153
Psyllium (35,000/kg)			0.034	1173	0.016	572
Salt (1,200/kg)	0.011	13	0.009	11	0.010	12
Sugar (4,000/kg)	0.020	80	0.017	67	0.017	70
Water (0 /kg)	0.348	0	0.482	0	0.479	0
Ingredient cost (UGX/kg dough)	**2080**		**2231**		**1675**	
Other costs 30% (UGX/kg dough)	624		669		502	
Total costs (UGX/kg dough)	2705		2901		2177	
Chapatis produced (#/kg dough)	11.1		11.1		11.1	
Revenue (UGX/kg dough)	5556		5556		5556	
Income (UGX/kg dough)	**2851**		**2655**		**3379**	

The demonstrations and information of this case show the potential of producing attractive, nutritious and affordable chapattis from local crops. Although the processing adjustments for the street vendors are very limited, training of street vendors and small holders in Uganda is foreseen by Bake for Life foundation to facilitate uptake.

Case 2. CRCs-based tin bread for artisanal bakeries in SSA

A processable and leavened dough can be prepared with a mixture of CRCs flours similar as for chapatti but with some adaptations (Table 7). The ratio of sorghum and cowpea flour can be varied to adapt to local taste and nutritional needs. Different varieties of sorghum and cowpea can be used, as locally available. Cowpeas are characterized by a beany flavour and beany odor. At the lowest level of inclusion (87g in 1000 g of CRCs flours), the beany flavour is only slightly perceived and may be acceptable up to the 270 g on 1000g of CRC flours (Table 7). Red cowpea varieties may be preferred to the white varieties as the beany flavour is less intense.

A brown and soft bread with a dense crumb can be obtained from the dough formulation indicated in Table 7. The breads were successfully produced at BBROOD, an artisanal bakery with shops in Kampala and Tororo (Uganda). This product has been deliberately called "Sccpy" instead of 'bread' to introduce it locally as a new product and thus avoiding the comparison with a white loaf.

Table 5 Basic formulation for CRCs-based tin bread.

Ingredients	**Dough with low cowpea content grams**	**Dough with high cowpea content grams**
CRCs flours mixture	*1000 of which*	*1000 of which*
Sorghum flour	457	274
Cassava flour	457	457
Cowpea flour	87	270
Dry yeast	50	50
Salt	23	23
Rapeseed oil	37	37
Sucrose	37	37
Psyllium flour	73	73
Water	1087	1087
Total	*2308*	*2308*

To prepare the breads, the flours mixture is placed in a close container together with the water for about 2 hours. This is performed to minimize sandiness associated to wholemeal sorghum and cowpea flours. After 2 hours, the flour and water mixture is added to the bowl of a spiral mixer and the remaining ingredients are added. Mixing is then performed for 5 minutes at low speed and for another 4 minutes at intermediate speed. Since, the CRCs flours do not contain gluten, mixing has the main purpose to ensure proper hydration of the mixtures into a homogeneous dough. After mixing, the dough can be divided and shaped manually, and put into greased baking tins. Each tin typically contains 700 g of dough. However, adaptations in the size of the dough pieces can be made as most convenient. The tins are then put to ferment in cabinets at 30 °C and 85% RH for 35 minutes. After proofing, the doughs are placed in an oven at 180 °C for 70 minutes. This basic procedure was followed at the BBROOD bakery in Kampala using the equipment available (Figure 5A). Breads from different sorghum and cowpea varieties were made (Figure 5B), thus indicating that this basic recipe can be adapted to different sources of locally available ingredients. Breads were offered to local customers (Figure 5C), who generally had a positive perception of the breads.

***Figure 5** Bakers at BBROOD bakery preparing the CRCs-based dough for tin bread baking (A); tin breads obtained from different varieties of sorghum and cowpea (B); slices of CRCs-based bread provided to local customers of the bakery shop for tasting (C). Figure adapted from Renzetti et al. 2022[12].*

Variations in sorghum and cowpea flour ratio can be used to modulate the sensory properties and the nutritional contents of the breads. A high cowpea flour content (Table 7) enhances bread volume and makes the crumb softer and moister than with low cowpea content. High cowpea flour inclusion also increases protein and fibre contents. The suggested ranges of cowpea inclusion are advised to optimize nutritional composition and taste.

The nutritional profile of the CRC-based breads with low cowpea content are compared to a commercial white bread in Table 6. The CRC-breads contain a substantial amount of dietary fibre, far above the content typically found in wheat bread. The protein content is lower than in wheat bread, mainly due to the high amount of moisture in the breads. An increase in protein content up to about 6.5% can be reached when the high cowpea content formulation of Table 7 is used.

***Table 6** Nutritional profile of white wheat bread and CRC-based breads.*

	White wheat bread (NL) *	NUTRIFOODS tinbread South African crops **	NUTRIFOODS tinbread Ugandese crops **
Energy (kJ/100g)	1046	863	881
Moisture (g/100g)	37.3	44.0	44.6
Protein (g/100g)	9	4.24	4.78
Nitrogen (g/100g)	1.4	0.678	0.764
Carbohydrates (g/100g)	47.8	33.9	33
- Sugars (g/100g)	2.2	< 0.5	< 0.5
Total dietary fibre (g/100g)	2.5	13.1	11.2
Fat total (g/100g)	1.6	2.95	3.86
- Saturated- (g/100g)	0.3	1.19	1.50
- Monounsaturated- (g/100g)	0.5	1.2	1.59
- Polyunsaturated- (g/100g)	0.6	0.553	0.763
- Omega 3 (g/100g)	0.1	< 0.1	< 0.1
- Omega 6 (g/100g)	0.5	0.526	0.716
- Trans fatty acids (g/100g)	0	< 0.1	< 0.1
Ash (g/100g)	1.8	1.78	2.14
Sodium (mg/100g)	418	355	441

*** Data from Dutch food composition table NEVO**

**** Analysed, courtesy of Prof. Henriëtte L. de Kock, University of Pretoria**

Case 3: Gluten-free bread (The Netherlands)

Commercial gluten-free breads under the brand name Yam are sold in the Netherlands on supermarket shelves as fresh breads with about four days of shelf-life. The commercial bread is mainly composed of oat flour, tapioca starch and soy flour. This commercial product was reformulated to make use of the CRC flours sorghum, cassava and cowpea (Table 8).

Table 8 Formulation of gluten-free bread for commercial application in the Netherlands using CRC flours.

Ingredients	grams
CRCs flours mixture	*1000 of which*
Sorghum flour	470
Cassava flour	470
Cowpea flour	60
Dry yeast	52
Salt	23
Rapeseed oil	38
Sucrose	38
Psyllium flour	75
Carboxy Methyl Cellulose	29
Water	1180
Total	*2435*

This formulation was developed and tested with Bakker Wiltink, the industrial gluten-free bakery that produces the Yam products. Compared to the commercial Yam products, the CRC-based bread showed increased bread volume, and a softer and less chewy crumb texture. These are positive differences that suggest the potential for commercial implementation as gluten-free products in the Netherlands and in Europe more in general. The brown colour and the more complex flavour profile due to the presence of wholemeal flours make these gluten-free breads also a potential alternative to wholemeal wheat breads .

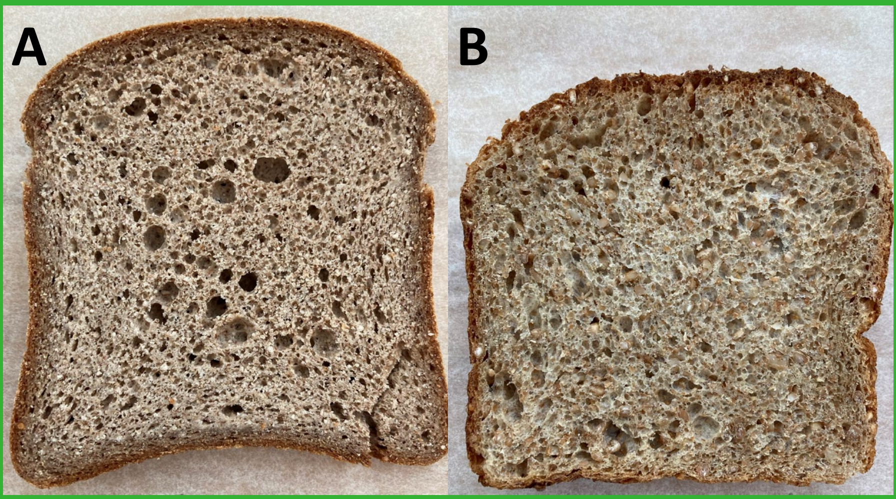

Figure 6 Slice of CRC-based gluten-free bread (A) compared to a commercial wholemeal wheat bread (B).

Consumer tests were performed in the Netherlands comparing the CRC-based bread with a commercial wholemeal wheat bread[11]. The CRC-bread product was clearly distinct from commercial wholemeal wheat bread with regards to texture and taste. Nevertheless, over 60% of consumers scored the overall "liking" of the CRC-bread from neutral to very much liked. Focused interviews with a limited number of Dutch consumers that regularly consume bread indicated that the taste of the CRC-bread product was generally appreciated as a positive characteristic of this bread. From a nutritional perspective, the CRC-bread provides a substantially higher amount of dietary fibers compared to commercial gluten-free breads in the Dutch market (Table 9).

Table 9 Nutritional composition of CRC based tin breads compared to gluten-free bread.

	Gluten-free brown bread (NL)*	NUTRIFOODS tinbread South African crops**
Energy (kJ/100g)	933	863
Moisture (g/100g)		44.0
Protein (g/100g)	6.6	4.24
Nitrogen (g/100g)		0.678
Carbohydrates (g/100g)	37	33.9
- Sugars (g/100g)	2.5	< 0.5
Total dietary fibre (g/100g)	6.9	13.1
Fat total (g/100g)	3.6	2.95
- Saturated- (g/100g)	0.4	1.19
- Monounsaturated- (g/100g)		1.2
- Polyunsaturated- (g/100g)		0.553
- Omega 3 (g/100g)		< 0.1
- Omega 6 (g/100g)		0.526
- Trans fatty acids (g/100g)		< 0.1
Ash (g/100g)	0.8	1.78
Sodium (mg/100g)	640	355

*** Data from Dutch food composition table NEVO**

**** Analysed, courtesy of Prof. Henriëtte L. de Kock, University of Pretoria**

Overall, the CRC-bread formulation is ready to be commercially implemented since it can be produced at industrial scale. This provides opportunities for CRCs in the EU market. The CRC-based gluten-free bread can attract consumers seeking for new tasty gluten-free bread products based on flour combinations which are unique in the market. Additionally, they can attract consumers seeking for alternatives to wheat breads.

8 Conclusions

The growing dependency of Africa on imported wheat to feed the population is a huge economic problem and makes the African food system highly vulnerable to disruptions like the wheat crisis due to the Ukraine-Russia war. **It is important to reduce Africa's dependency on imported food and to empower African economies to produce food products based on local, climate-reslient crops**. However, the trend towards increasingly using wheat and commodity crops for food production at the expense of indigenous crops is complex and multifaceted and therefore difficult to reverse: a fundamental transformation in the food system is needed.

This research entails a technological approach for utilizing local crops into attractive, nutritious and affordable food products. This development is considered highly relevant and promising from a food system perspective, linked with socio-economic and environmental drivers and contributing to nutrition security and a sustainable development. Implementation of our results can contribute to enhance use of local crops and clearly provide nutritional, economical and sustainability improvements and contribute to the desired **transformation towards a more resilient food system.**

Where single crops may have specific limitations in practical use and/or in certain nutritional aspects, we show that designing mixtures of local flours is a relative simple but very effective approach to optimize the use of local crops in many aspects:

- Combining the different functional properties of different local crops allows full replacement of wheat in bread-type products;
- Single crops may lack certain nutrients, but a combination of local crops can provide highly nutritional products. More specific the combination of cereals and pulses and the focus on wholegrain flours are beneficial in increasing nutrient quality;
- Combining different crops allows to balance the cost of the product in relation to other product aspects, to retain affordability. With the current high wheat price, a clear improvement of food affordability can be achieved in Uganda;
- Combination of local crops provide several environmental advantages like reduced fertilization, improved soils and biodiversity and will contribute to food security in the face of climate change, while using less resources, since they are adopted to the African climate and conditions. It offers opportunities to cultivate these crops in heterogeneous agronomical systems, in particular with pulse-cereal combinations;
- A versatile combination approach offers flexibility in developing food value chains depending on the local conditions and traditions. Furthermore, it reduces the dependency to a specific crop, mitigating the risk when a certain crop is not available, or temporarily too expensive;
- The consumer can be provided with a wide variety of attractive and nutritious foods based on local produce without compromising on taste or convenience demands in an urbanizing context;
- The functionality of Climate-Resilient Crops can be enhanced by low-cost technologies such as dry-heating, roasting, extrusion and fermentation to provide a variety of value-added, safe ingredients for food production.
- Value-adding activities on a variety of local crops offers new commercial opportunities, in particular for SMEs in the informal market. These activities can create jobs and employment along the food supply chain.

Mixtures of CRCs have been shown to provide an alternative to wheat and can provide affordable, nutritious food to low-income consumers. Current implementation and commercialization of these results in Uganda focus on setting up supply chains and development of consumer products. Short term implementation in other countries is highly feasible by formal as well as informal businesses. **Priority for implementation should first and foremost address countries which are both highly dependent on imported wheat as well as highly affected by climate changes.** These countries are most vulnerable to biological as well as geopolitical stresses and urgently require strengthening of the resilience of their food system.

9 Future prospects

This white paper clearly demonstrates that it is possible to make attractive, convenient and nutritious products based on local climate-resilient crops, instead of imported wheat. Hence, we demonstrate the opportunity to start building food value chains relying on domestic production, processing and consumption, which offers large advantages for local economies and improves self-sufficiency at the same time. Three attractive bread-type products based on local crops are presented as case examples, which were well accepted by food producers as well as consumers, demonstrating the potential of the approach. Nonetheless, several improvements are needed to stimulate and mature the use of local crops in bread-type products:

The current maturity level of ingredient processing (trade, milling and grain processing) is low, and needs further development to **increase local ingredient quality** and functionality. A particular aspect to improve is for instance the tendency of some grains and pulses to give rise to sandiness feeling in a food product, a phenomenon not well understood yet. It can be counteracted by for instance pre-soaking as reported in this paper, but grain processing techniques could be a step to develop next generation local crop ingredients and start new business activities. As suggested in this research low-cost technologies such as dry-heating, roasting, extrusion and fermentation could be highly suitable techniques.

The current replacement of wheat by a mixture of local crops still requires a small amount of a functional ingredient, psyllium fibre, which can be cultivated in Africa, but for its current supply Africa relies on imports from Pakistan and India. Reviving cultivation and processing of psyllium in arid areas in Africa could be an interesting opportunity for new economic activities. Alternatively, optimization and developments in bread **product formulations** could target full or partial replacement of psyllium. Since psyllium is a relatively expensive ingredient, finding replacement for this ingredient would be beneficial for product cost and food affordability.

A wide use of local crops in the food production sector is needed to increase the demand for local crops substantially, and to support the development of supply chains. We already report three very different bread-type products for different consumer segments, and further **product diversification** is needed. In particular development of popular convenient foods like mandazi's and other on-the-go bread type products are highly recommended.

Our results indicate that the formulation approach provided is versatile. Several exchanges of different cultivars or ingredient grades in the recipes resulted in good quality products. However, flexibility to **adopt a wider variety of local crops** depending on their local availability and price should be pursued in further research into the functional properties of a wider variety of climate resilient crops, to valorise their use. These activities could go hand in hand with co-creation processes with local food processors making use of local knowledge and traditions and involve local consumers to effectively guide development of local food supply chains in Africa.

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