Fighting Fe deficiency malnutrition in West Africa: an interdisciplinary programme on a food chain approach

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Abstract

About 2 billion people, mainly women and young children, suffer from iron deficiency. The supply of iron (Fe) falls short when consumed foods have a low Fe content or when absorption of Fe is inhibited by the presence of phytic acid and polyphenols in the diet. Current interventions are dietary diversification, supplementation, fortification and biofortification. In West Africa these interventions have only moderate chances of success due to low purchasing power of households, lack of elementary logistics, lack of central processing of food and the high heterogeneity in production and consumption conditions. A staple food chain approach, integrating parts of current interventions was proposed as an alternative. The research was carried out in several villages in Benin and Burkina Faso to take ecological, cultural and socio-economic diversity into account. The interdisciplinary approach aimed at elaborating interventions in soil fertility management, improvement and choice of sorghum varieties and food processing, to increase Fe and decrease the phytic acid-Fe molar ratio in sorghum-based foods. The phytic acid-Fe molar ratio was used as a proxy for Fe bioavailability in food. Synergy and trade-offs resulting from the integrated approach showed its added value. P fertilization and soil organic amendments applied to increase yield were found to also increase phytic acid content of the grain and thus to decrease its nutritional value. Amounts of Fe and phytic acid and their ratio in the grain differed among sorghum varieties, illustrating the presence of genetic variation for Fe bioavailability. The current local food preparation method for one of the main sorghum-based foods (*dibou*) in northern Benin did not include processing steps that remove or de-activate anti-nutritional factors reducing Fe bioavailability. The preliminary results suggest that a feasible chain solution consists of breeding for high Fe and moderate phytic acid contents and using soil organic amendments and P fertilization to increase yields but that this needs to be followed by improved food processing to remove phytic acid. Further research on timing of application of phosphate, Fe fertilizer and soil organic amendments is needed to improve phytic acid-Fe molar ratios in the grain. Research on the exact distribution of Fe, phosphate, phytic acid and tannins within the sorghum grain is needed to enable the development of more effective combinations of food processing methods aiming for more favourable phytic acid-Fe molar ratios in sorghum-based food.

Additonal keywords: anaemia, bioavailability, nutritional quality, diet, processing, phytic acid, agronomic practices

Introduction

About 2 billion people are affected by iron (Fe) deficiency, making it by far the most prevalent form of malnutrition. In 1989 it was estimated that 60% of the pregnant women, 45% of the non-pregnant women, 50% of the children and adolescents and only 25% of the men in developing countries were anaemic (De Maeyer *et al.*, 1989). One of the World Summit for Children's goals (1990) reported by UNICEF (Anon., 2000a) was the *reduction in 2000 of Fe deficiency anaemia in women by one third of 1990 levels.* In the mid-1990s, prevalence among pregnant women in Sub-Saharan Africa was estimated to be still as high as 44% according to UNICEF (Anon., 2000a), while ACC/CSN (Anon., 2000b) reported this prevalence to range from 47% in the east to 56% in the west of Africa. In pre-school children in Africa, anaemia prevalence ranged from 42% in West to 53% in East Africa (Anon., 2000b). In this paper we report on experiments in the context of a new interdisciplinary approach to reduce micronutrient malnutrition in two West African countries, Benin and Burkina Faso, both having serious Fe deficiency (Anon., 2004a).

The iron deficiency problem

Iron (Fe) is essential for the formation of haemoglobin in red blood cells, responsible for oxygen transport, and of certain enzymes in the human body. Red blood cells live about four months, so they have to be replaced constantly. The body can store some Fe in tissues and recycle some Fe when red blood cells die. However, as only one third of the body Fe can be stored, a continuous supply must be absorbed from the diet to retain health.

Fe deficiency causes anaemia, impairs mental development and decreases immunity. It has adverse effects on learning, productivity and, thus, earnings. Anaemia during infancy or childhood is associated with significant loss of cognitive abilities, decreased physical activity, and reduced resistance to disease. Fe deficiency in women of child-bearing age increases hazards associated with complications of pregnancy, premature birth and low birth weight, and leads to newborns with sub-optimal Fe reserves.

Women have high needs for Fe during pregnancy (Table 1) and lactation. Also young children have high Fe requirements because Fe is needed for growth. Any blood loss also increases Fe needs. While blood loss due to menstruation is unavoidable, blood loss due to internal (worms, flukes) and external (mites, lice, ticks) parasitic infections or to diseases such as malaria and HIV/AIDS can be reduced by improved hygiene, adequate prophylaxis, and timely and adequate treatment.

Table 1. Iron (Fe) intake requirements for different gender and age groups, from diets with 5 or 15% iron bioavailability. (Source: Anon., 1988; 2002).

Gender	Age group	Iron intake requirement	
		5% Fe bioavail.	15% Fe bioavail.
		(mg per day)	
Children	7–12 months	19	6
	1–6 years	13	4
	7–9 years	18	6
Boys	10–14 years	29	10
	15–18 years	38	12
Girls	10–14 years [1]	28	9
	10–14 year	65	22
	15–18 years	62	21
Men	> 19 years	27	9
Women	19–50 years [2]	59	20
	> 51 years	23	8
lactation	0–12 months after childbirth	30	10
pregnancy [3]	14–50 years		27

[1] Non-menstruating.
[2] Pre-menopausal.
[3] Source: Anon., 2001b.

Theory about how to increase effective supply of micronutrients

Besides reducing avoidable losses of body Fe, increasing the Fe supply is important to prevent or remedy Fe deficiency. The effective supply of micronutrients depends on three elements: (1) the intake of food, (2) the nutrient content of food, and (3) the bioavailability of these nutrients (Figure 1). Bioavailability is the proportion of ingested nutrients available for metabolic processes and storage in humans. Absorption of Fe from food depends on the form in which Fe is present and on the presence of enhancers and inhibitors in the same food item or in the same meal.

There are two forms of Fe in food: haem-Fe present in blood and meat and non-haem Fe present in plants, eggs and milk. About 35% of all haem-Fe consumed in the diet is finally absorbed. The non-haem Fe is usually present as complex inorganic salts. During digestion this inorganic Fe is partly reduced to the more readily absorbed ferrous (Fe^{2+}) form. The human body may actually absorb less than 5% of the non-haem Fe consumed. From the Fe in cow's milk about 10% is absorbed but from the Fe in breast milk, which is a special case, breastfed children absorb about 50%.

Absorption of non-haem Fe is increased by meals including foods rich in ascorbic

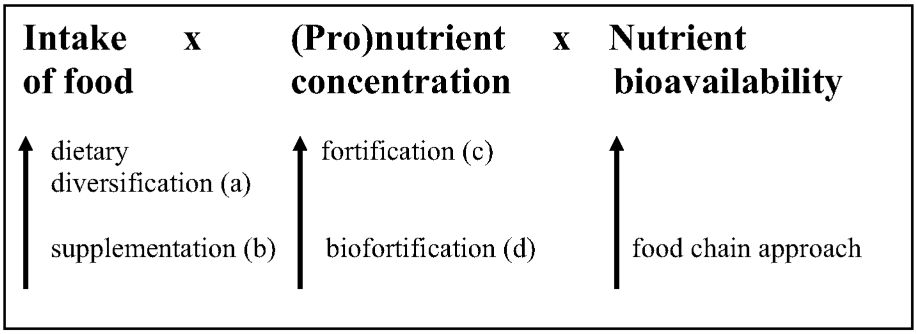

Figure 1. The three steps determining the effective supply of nutrients, the four current strategies (a–d) and a fifth new strategy impacting on these steps. (Source: C.E. West, unpublished).

and citric acid, like oranges (Wienk, 1996), and foods rich in haem-Fe, like meat. Tannin and phytic-acid-rich beverages and foods such as tea, wine, cereals and beans, when taken together with meals, may reduce Fe absorption (Hazell & Johnson, 1987; Hallberg & Hulthen, 2000). Enhancers and inhibitors can counteract each other's effects on Fe absorption.

Approaches to increase efficient supply of iron

Three strategies are currently in practice to improve Fe supply: (1) dietary diversification, (2) supplementation (Bothwell, 2000), and (3) fortification (Merx *et al.*, 1996). They interfere at different levels (Figure 1). Dietary diversification aims to increase the availability and intake of food that is rich in bioavailable Fe. Supplementation provides Fe sources in the form of pills and suchlike, additionally to daily diets. Fortification enhances levels of bioavailable Fe in frequently consumed foods either by adding Fe or by decreasing the effects of inhibitors. A fourth, more recent strategy aims to increase Fe in plant-based foods by breeding for micronutrient content (biofortification). They all contribute to solving the problem, yet they require certain conditions to be successful.

In the context of Benin and Burkina Faso, where our programme focuses on, there are many difficulties for application of the mentioned strategies.

Dietary diversification is based on improving the main daily diet. In Benin and Burkina Faso the daily diet is dominated by cereal or tuber/root staple crops for energy supply, with pulses acting as protein sources. Both, cereal staple crops and pulses contain considerable amounts of anti-nutritional factors reducing Fe absorption. Sorghum for instance contains only low amounts of Fe and two known inhibitors of Fe absorption: tannins and phytic acid. There seems to be ample scope for improving the supply of bioavailable Fe through dietary diversification, including meat and vitamin-C-rich vegetables and fruits in the diet. But food items rich in haem-Fe (meat, fish) are expensive and vitamin-C-rich vegetables and fruits (enhancers) are only available during a short period of the year. These constraints make it difficult to increase their intake.

Supplementation programmes have been implemented with good results in countries with well organized health systems. Distribution of Fe-foliate supplements to pregnant women is a feasible strategy because of its proven impact on anaemia and the low cost of the supplement. In developing countries daily compliance of the target group is hard to assure, lack of adequate infrastructure makes supplementation expensive and vulnerable to disrupted stocks while proper timing of supplements is difficult when populations hardly ever have contact with official health care infrastructures (Bothwell, 2000). For instance, in Benin there is only one doctor to every 6590 inhabitants, and the situation is worse in rural areas. Only 60% of the children in Benin received WHO-recommended vaccinations (Ategbo & Dop, 2003). Good results have been achieved with external funding, but programmes stopped as soon as donors withdrew.

Rural population hardly buys processed foods except oil, sugar and salt, which are thus suitable vehicles for fortification. Absence of centralized food processing units limits the possibilities for fortification of local products. However, fortified products may be imported. When followed by adequate dosage-control, distribution and pricing the use of fortified products may be successful for certain target groups. A successful example is iodine-fortified salt.

Considering the high contribution of staple foods to daily meals and their contribution to inhibiting Fe absorption, it seems relevant to try to improve Fe availability through activities focusing on staple crops. The recent approach of biofortification is implemented by the Consultative Group on International Agricultural Research (CGIAR). Their *Harvest Plus* programme aims at increasing Fe, zinc (Zn) and vitamin A and decreasing the amounts of phytic acid in a number of staple crops through modern breeding and selection techniques, including genetic modification. Although technical progress is made in some crops (e.g. Potrykus, 2003), several constraints make the approach less appropriate for Sub-Saharan Africa. Firstly, this part of Africa is characterized by a high heterogeneity in soil, climate and management conditions and a non-centralized seed supply system. This situation asks for development of many improved varieties, each fitting a specific set of variables. This makes biofortification very costly and asks for the development of a well organized seed production and distribution system if poor people in remote areas are to be reached with these improved varieties (Ndjeunga, 1997).

Secondly, post-harvest treatments including food processing can improve or undo the results of breeding. In Sub-Saharan Africa most post-harvest treatments take place in the individual homesteads of the producers, implying a high number of locally specific practices with unknown effects on Fe supply from staple foods. Finally, as anywhere else, nutritionally improved genotypes may be rejected because of agronomic disadvantages, consumer dislikes or other socio-cultural aspects.

The strong points of the above-mentioned four strategies can be combined into a coherent integrated food chain approach with ample attention to the biophysical, political and socio-economic circumstances constraining or enabling its implementation. In Benin and Burkina Faso, countries with little adequate infrastructure, interventions should aim at locally produced and consumed staple foods like sorghum and millet. This avoids problems related to logistics that dominate supplementation and fortification approaches. Improving the quality of these staple foods (including the biofortification approach) reduces the need for rural households to purchase or produce additional Fe-rich foods or enhancers as proposed in the dietary diversification approach. Exploring adaptations of local practices and including producers, processors and consumers as actors in a combined approach offers opportunities to find solutions that have a high chance of adoption.

Based on the food chain approach, Wageningen University in the Netherlands initiated and proposed funding for a joint research programme to be elaborated with institutes in Benin and Burkina Faso (and in China). The programme is financed by the university's Interdisciplinary Research and Education Fund (INREF). This fund also covers other interdisicplinary North-South research programmes. The programme is called 'From natural resources to healthy people': food-based interventions to alleviate micronutrient deficiencies (Anon., 2001a) and runs from 2001 until 2006. Below we shall describe the programme approach, followed by literature reviews leading to relevant research questions and preliminary results. In a later section the results will be discussed and the approach will be evaluated.

A programme based on a food chain approach

The food chain approach

The food chain approach is represented by Figure 2, which forms the framework for the programme (Anon., 2001a). The complete programme focuses on improving Fe and Zn supply through staple foods in West Africa and China. This paper mainly reports on Fe and phytic acid in sorghum staple food in West Africa although some results on zinc will be mentioned in the agronomic part. The boxes in the middle of Figure 2 form a chain representing the flow of Fe, Zn and phytic acid from natural resources (soil) to the human body (health). Enhancers are only considered in the domain of dietary composition.

Breeding, agronomic practices, storage, food preparation and processing, and dietary composition are possible interventions. Plant and soil factors influence the availability of Fe for uptake by plants. Actual uptake can further be stimulated by soil management measures. Varieties differ in their ability to take up micronutrients from the soil or to transport micronutrients and phytic acid to the grain. Knowledge of plant physiological processes and assessment of ranges of difference in Fe and phytic acid contents in the grain are essential for developing a breeding strategy aiming at varieties with favourable grain phytic acid-Fe ratios. Assessment of post-harvest activities is needed for proposing food processing methods that increase the contents of desirable micronutrients and remove or de-activate anti-nutritional factors, at the same time making attractive and digestible foods.

The inner circle of Figure 2 concerns decision-making and resource allocation by producers, processors and consumers of staple foods. In West Africa all activities regarding staple foods generally take place at household level. The household and its actors are therefore important units of research.

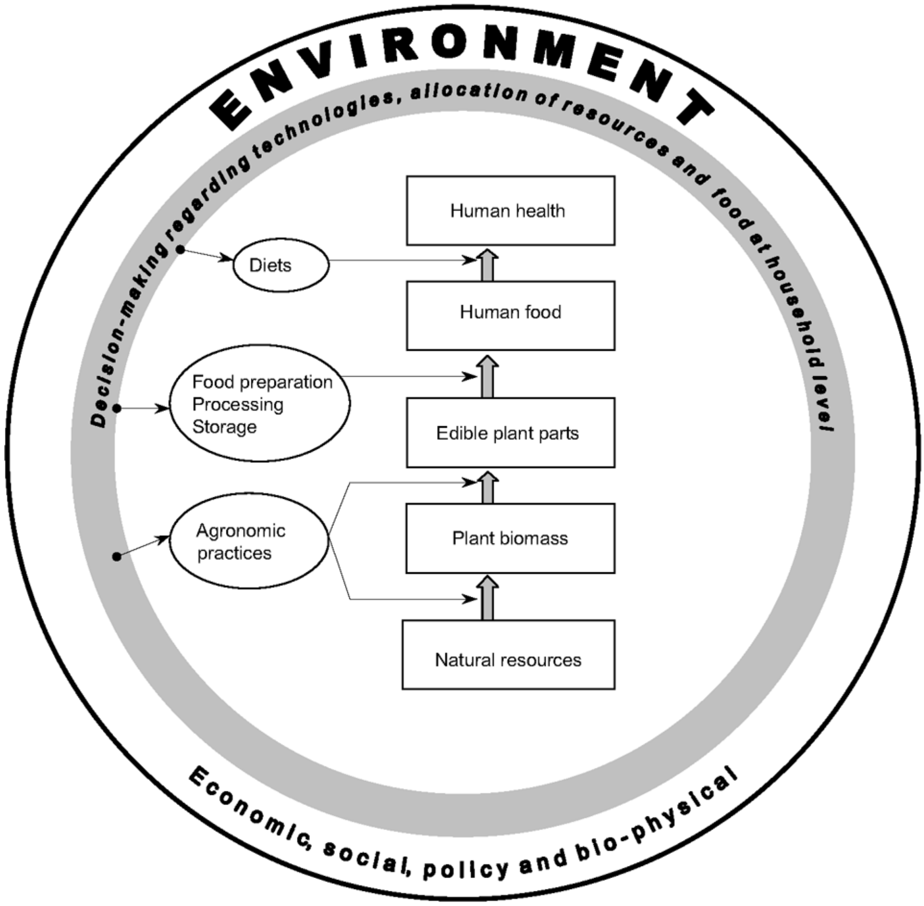

Figure 2. Analytical framework for the research programme: food chain approach and context.

The outer circle of the figure represents the 'environment'. In West Africa the biophysical environment consists of poor soils and of rainfall patterns that are highly irregular both in time and space, making high and sustainable food production difficult. The economic environment is characterized by lack of infrastructure (roads, irrigation facilities and financial institutions), lack of affordable inputs (fertilizers, pesticides), low purchasing power of both producers and consumers and thus lack of attractive markets and large price fluctuations between seasons and between years. Such an environment is characterized by high transaction costs. The social environment consists of a majority of poorly educated people with little clout towards governments and industries. The 'donor' environment consists of many developing organizations that work on all kinds of topics, such as the Helen Keller Foundation on home gardening, UNICEF in micronutrient supplementation programmes and the International Fertilizer Development Center (IFDC) working on nutrient management to increase crop yields, to name just a few. National policy documents show that the policy environment is aware of the micronutrient problem. However, national governments and their representatives at decentralized levels lack sufficient financial means, scientific insights or political power to co-ordinate these donor-initiated efforts or to choose from proposed interventions. One role of the research programme is to support decision-making by providing insight into the impacts of the different interventions and their adequacy in different environments. The programme will communicate with donor organizations and policy makers through scientific papers and contributions to regional and international conferences. Local farmers and food processors are included in the research and participate in discussions on the hypotheses, set-up and outcomes of parts of the research. These discussions will lead to the formulation of locally applicable recommendations for best practices.

The food chain approach applied

In the next sections we aim to provide arguments for three important pre-analytical choices: the choice for sorghum, the choice for Fe-deficiency and the choice for Benin and Burkina Faso as research locations. Next we shall consider the different interventions that are subject of our research. Each section includes a short literature review leading to the major research question and preliminary results. The first sections concerned provide details on the nutritional studies and serve to identify a sorghum consuming and Fe deficient population in which results of the programme can be tested through intervention studies. In the next section, soil and plant factors determining Fe availability and uptake by plants are discussed and the agronomic studies are introduced. Also plant breeding aspects are discussed and results of a screening experiment in sorghum will be presented. Finally, interventions at the level of food processing are highlighted. It is yet too early to have results on the verification of the found technologies through interventions by nutritionists. These results will be published later.

Diet: the importance of sorghum

In Africa, sorghum, millet, maize, cassava, plantain and yam are the staple crops; rice and pulses are locally important. We chose for sorghum as it is a dominant crop in the drier agro-ecological areas of Africa and because results of our efforts may also have implications for countries outside Africa, e.g. for India and China, where large populations depend on sorghum as well. Also, sorghum contains large amounts of polyphenols and phytic acid, which are responsible for inhibition of Fe absorption, not only from sorghum but also from other components of the diet. Addressing sorghum breeding in the programme is complementary to the CGIAR *Harvest Plus* programme that chose to work first on other crops. Before giving results from our work some figures are presented to show the importance of sorghum in the pre-selected countries of research.

Sorghum production is moderate (160,000 metric tons in 2003) in Benin as a whole but dominant in the northern part of the country, especially in the Atacora province. Other important crops in Benin are yam and maize. In the period 1998–2000 about 96% of the energy intake per capita per day (937 kcal) came from plant-based sources. On average, cereals provided 38% of this intake, root and tuber crops 37%, fruits and legumes 2.8%, and meat 2% (Ategbo & Dop, 2003).

Burkina Faso is a large sorghum producer with an annual production of 1.1 million metric tons in 1999–2003. The second most important crop in this country is millet followed by maize. About 95% of energy intake per capita per day (kcal) came from plant-based products, 5% from fish, meat and milk. In 1998, cereals contributed 76% to the energy intake, fruits and legumes 1% (Anon., 1998). In 1991 about 45% of the energy intake from cereals came from sorghum (Gillespie *et al.*, 1991). Average sorghum consumption per capita per year was 89.8 kg in 2001 and 87.0 kg in 2002 (Anon., 2004b), representing about 700 kcal per capita per day. In both Benin and Burkina Faso there are large differences between urban rich and rural poor and between regions.

In Benin the highest prevalence of child malnutrition is found in Borgou, Atacora and Zou provinces (Ategbo & Dop, 2003). Within the programme, sorghum consumption by children was investigated in three neighbouring villages in Atacora province during two seasons (pre-harvest and post-harvest). Food availability is lowest in the pre-harvest season (July–August), and highest in the post-harvest season (October–March). The contribution of sorghum to the diet of the rural population and their Fe status was investigated. Some results of the post-harvest study will be presented here.

A food consumption study was conducted by C.E.S. Mitchikpe (unpublished results) in a randomly selected sample of 80 children in the age of 6–8 years. The study, which was carried out during a 5-week period in November–December 2002, consisted of recording the weighed diets during periods of three consecutive days. A close look at the data showed consistent differences between observations from the first and the later part of the study period. So the study period was divided into two parts: the first half (period 1), from 25 November to 11 December, and the second half (period 2), from 12 to 28 December 2002 (Table 2). Apart from the foods listed in Table 2, rice flour, cooked and dried cassava, dried yam and beans were consumed, albeit in low quantities. Consumption of meat and vitamin-C-rich foods like fruits and vegetables was negligible. At the start of the study only maize was harvested (starting in August) explaining its dominance in the average daily diet in period 1. The contribution of sorghum and millet to daily food intake increased in period 2 as their harvest started in November–December. In both periods children consumed mainly fresh yam. The pre-harvest study gives more information on the absolute and relative importance of sorghum in the diet.

The diets encountered were of the category of low-bioavailability diets, based on cereals and tubers. They contained negligible quantities of meat, fish and ascorbic-rich foods, and thus hardly any absorption enhancers. Low bioavailability in this case means that on average only 5% of the Fe present in such diets can be absorbed by the human body (Anon., 1988). This will be elaborated on below.

The results show that sorghum is indeed a staple food in the villages and that its contribution to the diet increases after its harvest in December. The population may be

Table 2. Phytic acid and iron (Fe) contents of foods from specific food crops, and estimated daily intake of these foods in the first and the second part of the post-harvest period of 2002 in Atacora province, Benin. (Source: C.E.S. Mitchikpe, unpublished results)

Food group and food	Phytic acid [1]	Fe [2]	Average daily consumption		
			Total period n = 79	1st part [3] n = 39	2nd part [3] n = 40
	- - (mg per 100 g) - -		- - - - - - - - - - - - -(g per day [4]) - - - - - - - - - - - - -		
Cereals			167 ± 90	157 ± 106a[5]	176 ± 71b
Sorghum flour	446	10	38 ± 65	17 ± 38a	59 ± 79b
Maize flour		2	81 ± 83	107 ± 86a	55 ± 73b
Millet flour		4.2	29 ± 64	8 ± 30a	49 ± 81b
Tubers			315 ± 272	278 ± 218	350 ± 314
Yam, cooked	50	0.5	293 ± 273	262 ± 225	323 ± 313
Pulses			45 ± 64	55 ± 74	35 ± 51
Bambara groundnut	317	12.2	27 ± 42	33 ± 42a	21 ± 42b

[1] Source: Gibson, 1994; except for bambara groundnut: Akaninwor & Okechukwu, 2004.

[2] Source: Atacora food table, which is a compilation of data from Mali, Nigeria, Ethiopia and FAO and which has not yet been corrected with the analytical data from food samples collected in the villages under study.

[3] Subgroups were made of children recruited in the first part (25 November – 11 December) and in the second part (12–28 December). The data from one child in the first group were discarded because of inaccurate measurements.

[4] Means ± SD (between-persons variation).

[5] Means in the last two columns, followed by the same letter do not differ statistically ($P < 0.05$; Mann-Whitney).

a target for later intervention studies if data confirm their presumed low Fe status and if sorghum is indeed an important staple in the other periods of the year.

Health: the prevalence of iron deficiency

Data on Fe deficiency and Fe-deficiency-related diseases are scarce and measurements of people's Fe status even scarcer. We therefore shall use haemoglobin levels as indicators of anaemia and prevalence of anaemia as a proxy for Fe deficiency although other causes of anaemia exist. Table 3 shows the prevalence of anaemia in Burkina Faso in different years. The data from the CNN in this table are based on a survey in 15 provinces (Anon., 1997).

Table 3. Prevalence of anaemia [1] in Burkina Fasso. Data from four studies.

Source/ gender and age group	Anaemia prevalence	Severe form
	- - - - - - - (%) - - - - - - -	
Meda et al., *1993* (women; 15–49 years)		
Pregnant women (n = 56)	71.4	
Lactating women (n = 123)	64.2	
Non-lactating/non-pregnant (n = 72)	38.9	
Total women (n = 251)	58.6	
CNN (Anon., 1997)		
Children (0–5 years)	41.7	13.5
Children (5–10 years)	27.2	4.2
Men	25.2	6.9
Women	31.5	7.9
Meda et al., *1999* (women; 18–50 years)		
Pregnant women (n = 2308)	66	1.7
UNICEF (Anon., 2004a)		
Children (0–5 years)	83	
Women (14–49 years)	48	

[1] Criteria for haemoglobin levels. Pregnant women and children under 5 years: ≥ 110 g per litre blood; non-pregnant women and children from 6–14 years: ≥ 120 g per litre blood; men: ≥ 130 g per litre blood. Lower levels means anaemia; below 70 g per litre means severe anaemia (Gillespie *et al.,* 1991).

In 1995–1996, Meda *et al.* (1999) carried out a cross-sectional study on anaemia in pregnant women attending two antenatal clinics in the city of Bobo-Dioulasso, Burkina Faso. The results showed a prevalence of mild ($100 < Hb < 110$ g l^{-1}), moderate ($70 < Hb < 100$ g l^{-1}) and severe ($Hb < 70$ g l^{-1}) anaemia in 30.8%, 33.5% and 1.7% of the women, respectively. From logistic regression it appeared that anaemia was significantly and independently related to advanced gestational stage and low socio-economic status.

More recent data from Benin and Burkina Faso are based on partial surveys and statistical modelling techniques (Anon., 2004a) and show about equal prevalence of anaemia ($Hb < 110$ g l^{-1}) in children under 5 years of age: 82 and 83% for Benin and Burkina Faso, respectively. Of the reported anaemic children in Benin 9% had a severe form, 51% a moderate form and 22% a mild form of anaemia (EDSB, 2001; in Ategbo & Dop, 2003). Prevalence of anaemia in women between 14 and 49 years of age varied between 48% in Burkina Faso and 65% in Benin (Anon., 2004a).

Anaemia, and hence Fe deficiency, is certainly prevalent in the countries participating in the programme. Fe deficiency in children was further investigated in Benin

(C.E.S. Mitchikpe, unpublished results). Haemoglobin levels were measured in the same 80 children as mentioned above. The study showed that 35% of the children had haemoglobin levels below the minimum (< 115 g l^{-1}), with the cut-off point taken from Anon. (1988). The differences in haemoglobin level between boys and girls and among children sampled during different parts of the post-harvest period were not statistically significant.

The requirement to prevent anaemia in children from 6 to 12 years corresponds with an Fe intake of 6–9 mg per day depending on the bioavailability of the iron from the diet (Table 1; Anon., 2002). The measured haemoglobin levels indicate that Fe intake for the population studied was below the mentioned requirements but do not tell how much below.

The question is how to link the dietary composition to Fe intake and bioavailability and how to assess the contribution of sorghum. Food composition tables based on African foods can be consulted for Fe contents of maize, sorghum, millet, and yam-based foods and also of snack foods based on crops like Bambara groundnut (*Vigna subterranea*). The tables show that the Fe content of cereals generally is higher than that of yam and that raw Bambara groundnuts are considered a relatively good source of Fe (Table 2). Literature occasionally provides phytic acid data (Gibson, 1994; Akaninwor & Okechukwu, 2004) showing that yam has a low phytic acid content compared with cereals and Bambara groundnut. For the children in this study this means that although yam is consumed in large quantities, its contribution to Fe intake is moderate, while cereals and Bambara groundnut probably decrease Fe bioavailability in the meal due to their high phytic acid contents. The low consumption of Bambara groundnut may nevertheless still be of some importance thanks to its fairly high Fe content.

Since data from literature are not necessarily fully applicable to locally found foods, additional analyses of representative local food samples were carried out to adapt the data in Table 2 to the study area. These detailed analyses include Fe, the enhancer vitamin C and the absorption inhibitor phytic acid, to allow for a better estimation of the contribution of sorghum to the supply of bioavailable Fe in different seasons. This contribution will be related to the role of other food items in the diet.

So far sorghum can be considered an important source of iron. Part of the year it is daily consumed in considerable quantities and its Fe content is relatively high compared with that of the other components in the diet. However, its phytic acid content reduces its potential contribution to daily Fe supply, and children consuming sorghum-based diets were found to be Fe deficient. Therefore the other components of our programme aim to increase the Fe supply by decreasing the phytic acid-Fe molar ratio in the sorghum grain. This requires three steps: (1) agronomic practices, (2) breeding to produce sorghum grains with desired qualities, and (3) food preparation practices to further improve these qualities.

Agronomic practices

The full programme investigates effects of agronomic practices on Fe, phytic acid, tannins and Zn. Although this article reports specifically on phytic acid and Fe, literature findings on P and Zn that bear relevance to mechanisms influencing the phytic acid-Fe molar ratio in sorghum grain are highlighted as well.

The availability of micronutrients in soils for uptake by plants depends on soil pH, soil organic matter content, adsorptive surfaces of the rhizosphere, and physical, chemical and biological conditions in the rhizosphere (White & Zasoski, 1999). Bivalent Fe (Fe^{2+}) is much more available for uptake by plants than Fe^{3+}, so soil conditions favouring Fe^{2+} improve the availability of Fe to plants. Soil pH has a strong effect on the free iron content of the soil. In the pH range 5.5–7.0 an increase of one pH unit (for instance by liming) causes a 100-fold decrease in aqueous (i.e., free) Fe^{2+} content (Frossard *et al.*, 2000).

Plants can excrete substances modifying the rhizosphere. Examples are the release of H^+ ions by plant roots to decrease local pH (Marschner, 1995), which can be beneficial for micronutrient uptake by plants from alkaline soils, and the release of phytosiderophores (plant-produced chelators) from sorghum to increase Zn solubility (Hopkins *et al.*, 1998). The effect of phytosiderophores on Fe-uptake is yet unknown. Intercropping sorghum with other crops can be used as a strategy to increase micronutrient uptake by sorghum if the associated crop species modifies soil conditions.

The presence of mycorrhiza in the soil that are able to attach to plant roots, can lead to much higher adsorptive surfaces of the rhizosphere (Rengel *et al.*, 1999). Inoculation of sorghum plants with Vesicular Arbuscular Mycorrhiza (VAM) in a pot experiment with a West African P-deficient acid sandy soil led to higher P, but lower K, Ca, Mg and Zn contents in the sorghum shoot. Adding P fertilizer increased nutrient uptake by stimulating early root growth, thereby improving the possibilities for VAM infection, but decreased mineral contents even further because of the dilution effect of increased shoot dry matter (Bagayoko *et al.*, 2000). Although Fe was not measured, a similar effect on Fe contents may be expected from VAM and P fertilizer.

Soil organic matter decomposition affects the redox potential, leading to shifts between Fe^{3+} and Fe^{2+}. Decomposition of organic material can provide siderophores and fulvic acid, increasing Fe solubility. Decomposition under anaerobic conditions (waterlogging) may lead to highly soluble Fe^{2+} but also to the formation of bicarbonate, which together with Fe^{2+} leads to insoluble $ZnFe_2O_4$ (Rengel *et al.*, 1999). So waterlogging of sorghum in the presence of organic soil amendments, which can for instance occur in Zaï systems in Burkina Faso, can be either beneficial or detrimental to the soil's Fe supply.

Farmers can influence the environment of crop growth by choice and timing of inputs, choice of soil–plant combinations, and appropriate water management. Management includes the application of organic material and micronutrient fertilizers. Most soils in Africa are phosphate-deficient, so phosphate fertilizer application is widely advised to increase yields (Henao & Baanante, 1999). Application of phosphate fertilizer leading to higher millet yields also led to a higher phytic acid content and to a higher phytic acid-Zn molar ratio in millet grain and thus to a lower nutritional quality (Buerkert *et al.*, 1998). Other methods to increase yield, such as the application of crop residues, had no effect on the phytic acid-Zn molar ratio (Buerkert *et al.*, 1998). No data are available on the effect of phosphate fertilizer and crop residues on phytic acid-Fe molar ratio in sorghum. The literature review showed that no efforts had yet been made to explore whether yield-increasing measures such as organic soil amendments and P fertilizers had an effect on bioavailable Fe and Zn in sorghum grain. However, because of the increased phytic acid formation and the lower Fe and Zn contents in the grain due to the higher yield, there are reasons to hypothesize a positive effect of organic soil amendments on Fe and Zn uptake by the plants but a negative effect of P fertilizer on Fe and Zn bioavailability in the grain. The use of Fe or Zn fertilizers may change the results towards a more positive outcome.

One of the programme's studies, by K. Traoré, therefore addresses the following research question: *The effect of the amount and timing of organic soil amendments, phosphate fertilizer and Zn fertilizer on the Zn content, phytic acid content and phytic acid-zinc molar ratio in sorghum grain.* The research focuses on phytic acid and Zn and not on Fe for the following reasons:

1. Bioavailability of Fe and Zn are both highly influenced by the presence of phytic acid and information on phytic acid found in the proposed research will therefore also be relevant for Fe bioavailability;
2. There is relevant information in the literature on Zn and P fertilization in millet that can be used as basis and reference for experiments with sorghum;
3. The budget did not allow for extensive chemical analyses and a choice had to be made between Zn and Fe if also phytic acid content would be analysed.

Despite the focus on Zn, the results from this research provide valuable information for the fight against Fe deficiency malnutrition because often we can read Fe instead of Zn, and especially the results on phytic acid are relevant for both micronutrients. The research question was related to a popular local soil and water conservation technique called 'Zaï', which is known to increase yield. The 'Zaï' system implies the use of a 20–30 cm wide and 10–20 cm deep planting pit in which organic soil amendments are applied that provide nutrients and improve infiltration and storage of rainfall. Capturing run-off water from their direct surroundings, Zaï pits further increase water availability to the plants and decrease soil losses that are generally associated with run-off over large distances. The final objective of this research was to find simple and low-cost modifications of the Zaï system to increase sorghum quality (in terms of Fe and Zn content and bioavailability) while maintaining the yield gain under Sahelian soil and rainfall conditions.

The first step was a field survey on actual Zaï practices (Traore & Stroosnijder, 2005). Zaï appeared to occur on two soil types, sandy and gravelly soils, and pits were filled with two types of soil organic amendments, farmyard manure (FYM) and compost. Secondly, experiments were conducted in farmers' fields with Zaï pits with a focus on Zn, P and phytic acid in order to verify whether literature results found for Zn and phytic acid related to P fertilizer in millet (Buerkert *et al.*, 1998) would also be valid for sorghum. Results relating P fertilizer to phytic acid content are relevant for both Fe and Zn bioavailability.

In 2002, a field experiment was laid out in Somyaga on two soil types (a sandy and a gravelly soil), comparing the effects of FYM and compost, with or without triple super phosphate (TSP) and with or without $ZnSO_4$, on the phytic acid and Zn contents of sorghum grain. The experiment was of a completely randomized block design; plot size was 25 m^2. The locally popular, improved, drought tolerant sorghum variety IRAT

Table 4. Phytic acid content of sorghum grain as affected by soil type and organic soil amendments, without or with phosphate fertilizer [1]. (Source: K. Traore, unpublished results).

	Without P	With P
	------ (mg per g) ------	
Main factors		
Gravelly soil	2.27	5.94
Sandy soil	2.56	6.53
Compost	3.01	6.89
Farmyard manure	1.83	5.59
Phosphate fertilizer [1]	2.42	6.24
Interactions		
Gravelly soil × compost	2.71	6.44
Gravelly soil × farmyard manure	1.83	5.44
Sandy soil × compost	3.30	7.33
Sandy soil × farmyard manure	1.82	5.73

[1] Triple super phosphate.

204 was used. The trial was carried out on two farms, which resulted in a total of 32 experimental units. Compost was applied at a rate of 15 t ha^{-1} (50% dry matter), FYM at a rate of 10 t ha^{-1} (50% dry matter), TSP at a rate of 200 kg ha^{-1} (45% P_2O_5) and $ZnSO_4$ at a rate of 14 kg ha^{-1}. The soil was analysed for C, N, P, pH, CEC and Zn. The grain was analysed for phytic acid and Zn. The average phytic acid contents per treatment are summarized in Table 4. Analysis of variance was used to identify treatment effects.

The effect of TSP on phytic acid content was statistically significant ($P < 0.001$). TSP led on average to a higher phytic acid content across all treatments (Table 4). Organic soil amendments also significantly contributed to differences in phytic acid ($P < 0.02$). Influence of soil type and interactions between treatments were not statistically significant. The effect of TSP on phytic acid content indicates that part of the P from the TSP fertilizer was converted into phytic acid. The results of Lott *et al.* (2000) pointed in the same direction. Fertilization with TSP may thus reduce bioavailability of Fe and Zn. As the amount of bioavailable micronutrients depends on the phytic acid-micronutrient molar ratio, conclusions cannot be based on phytic acid alone; also the absolute Zn content in sorghum grain should be taken into account.

Figure 3 shows the results for the same experiment in 2003 with control treatment (–Zn/–P), either Zn (+Zn/–P) fertilizer or P fertilizer (–Zn/+P) and both fertilizers (+Zn/+P).

Figure 3A shows that compared with the control treatment (–Zn/–P), P fertilizer alone, Zn fertilizer alone, and P plus Zn fertilizer all led to an increase in grain yield and an increase in total Zn yield in sorghum grain per hectare. Also total phytic acid in grain per ha increased with fertilizer application (Figure 3B). Nutritional quality

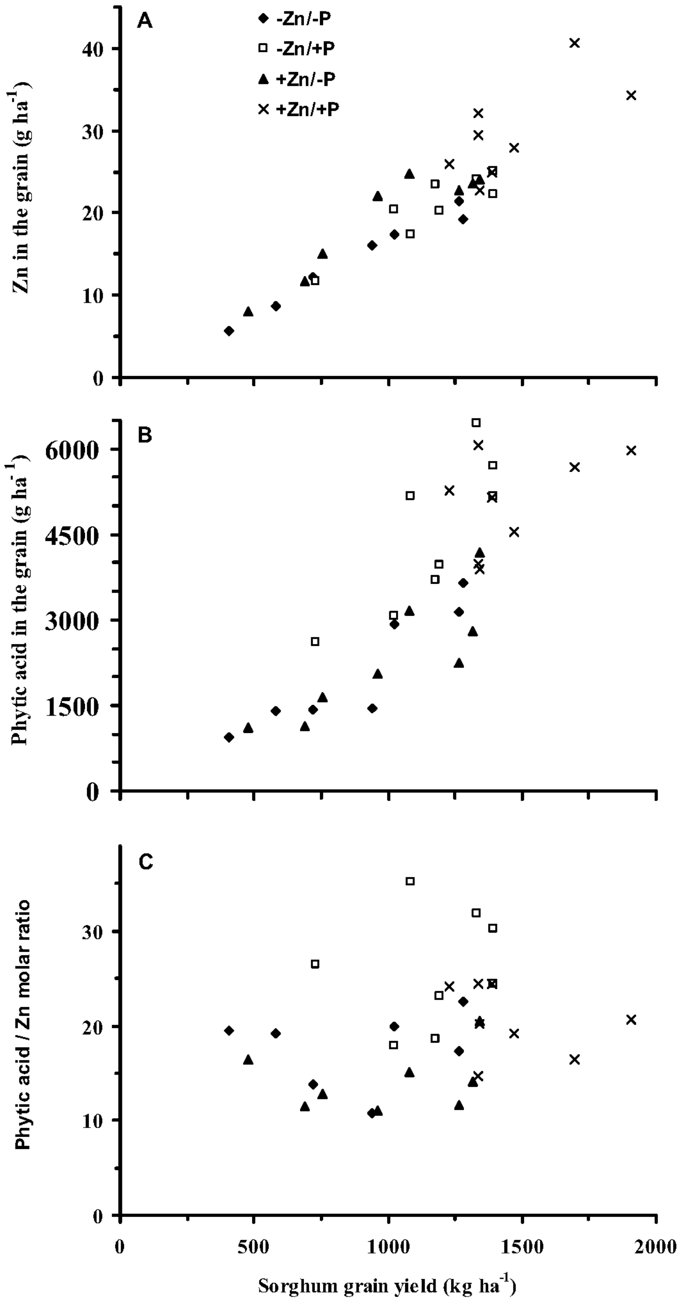

Figure 3. Effect of Zn and P fertilizer on the relation between sorghum grain yield and (A) Zn in the grain, (B) phytic acid in the grain, and (C) the phytic acid / Zn molar ratio. Results from the Somyaga field experiment 2003. (Source: K. Traore, unpublished results)

expressed as phytic acid-Zn molar ratio was thus influenced by P and Zn fertilization. The +P/–Zn treatment showed the highest ratio, indicating that the increase in phytic acid due to P fertilization was not compensated by the slight increase in Zn content and led to lower nutritional quality. For the +P/+Zn treatment the ratio was lower as Zn fertilizer apparently led to more Zn to be loaded into the grain, improving nutritional quality. These trends were found over a range of grain yields. The ratio was lowest for the –P/–Zn treatment and thus most favourable for human nutrition. But in that case the total yield and the total amount of Zn in this yield per hectare were low too.

The tendencies observed concerning yield, phytic acid and Zn content and the phytic acid-Zn ratio were confirmed in experiments in 2002 and 2004 although some interaction with rainfall seemed to occur.

To further explore the effect of P fertilizer on phytic acid formation pot experiments were conducted with timing of P fertilizer as treatment. Considering that the decomposition of organic material under waterlogged conditions improves Fe solubility (Rengel *et al.*, 1999), that the Zaï system tends to accumulate run-off water, and that the results over 2002 and 2004 (Figure 3) seemed to depend on rainfall conditions, additional pot experiments were planned. These experiments served to test the effect on micronutrient–phytic acid content in sorghum grain of applications of organic material with different water regimes and with and without micronutrient fertilizer. Regular harvests and analyses of plant organs during sorghum growth and development will allow monitoring micronutrient, P and phytic acid fluxes in the plant, giving insight into the contribution of different processes (uptake, transport, re-allocation) to the final micronutrient-phytic acid molar ratio in the grain.

Breeding and physiology

Possibilities to influence micronutrient and phytic acid content in sorghum grain by management practices were highlighted above but the effects were investigated with only one locally popular sorghum genotype. Literature was searched to find out whether genotype differences have been reported for polyphenol (or tannin), Fe, Zn and phytic acid contents. In the context of this paper, we shall focus on Fe only.

Dicko *et al.* (2002) analysed 50 sorghum varieties from Burkina Faso and found polyphenol contents to vary between 1.31 and 27.19 mg g^{-1} and tannin contents to vary between 0.01 and 19.77 mg g^{-1}. Many but not all polyphenols and tannins act as anti-nutritional factors. Hulse *et al.* (1980) found Fe contents to vary between 0.5 and 25 mg per 100 g but most sources do not report more than 14 mg per 100 g. Doherty *et al.* (1982a) found phytic acid contents of 2.57–3.80 mg per g dry weight in 24 Indian sorghum samples, with phytic acid-P content varying between 73 and 95% of total P. Frossard *et al.* (2000) reported much higher phytic acid contents, ranging from 9.1 to 13.5 mg g^{-1} in dry sorghum samples. So large differences among genotypes have been reported.

A problem is that literature does not provide information per genotype for the four components at the same time: Fe, Zn, polyphenol (or tannin) and phytic acid. Information is incomplete and scattered and the genetic component is hardly ever separat-

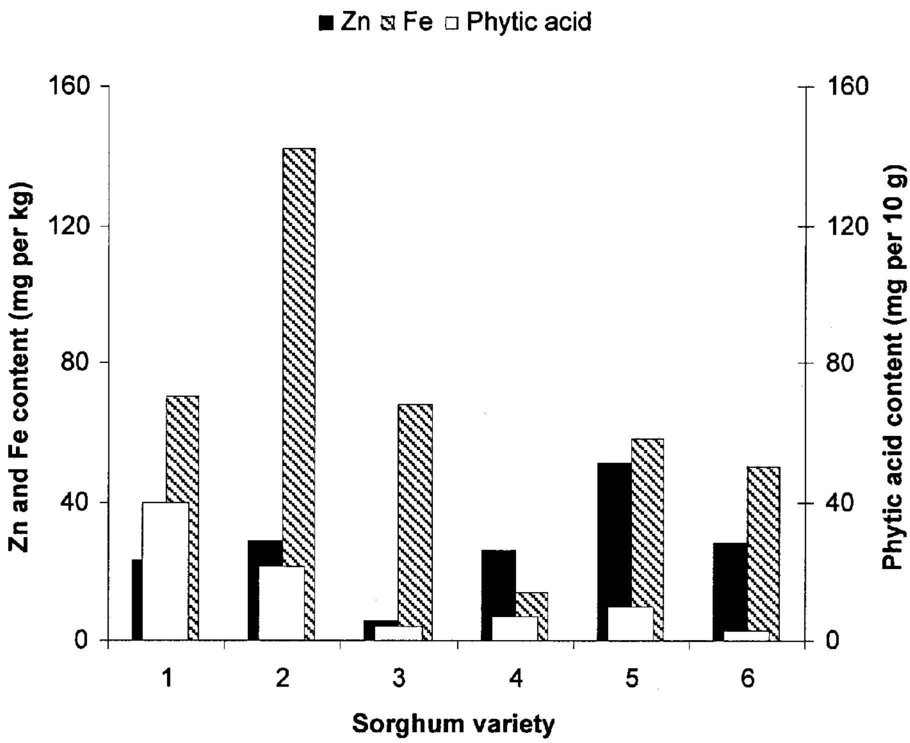

Figure 4. Zinc, iron and phytic acid contents of the grain of six contrasting sorghum varieties selected from the CIRAD sorghum collection at their field station at Samanke, Mali, in the 2002–2003 season. (Source: M.A. Slingerland, unpublished results)

ed from environmental and management effects. Therefore the programme decided to screen the sorghum core collections of ICRISAT and CIRAD. All 210 varieties were multiplied at Samanké research station of ICRISAT in Mali during the off-season of 2002–2003 in one environment (soil, climate) and under identical management conditions. A selection of the data is presented in Figure 4.

Based on these data the programme will select sorghum varieties with genetic potential for high Fe and moderate phytic acid contents (e.g. variety 2 in Figure 4) or for moderate Fe contents and low phytic acid (e.g. variety 3 in Figure 4). These varieties will be compared in agronomic experiments exploring the effect of genotype × environment interactions on phytic acid-Fe molar ratio in the grain. Grains of contrasting quality will be used in feeding trials in humans, to be performed in Benin and in Burkina Faso, to verify the effect of genotype on Fe bioavailability in humans. Some of the contrasting sorghum varieties will be further investigated in breeding experiments.

Breeding can aim at maximum Fe content and/or minimum content of anti-nutritional factors, as a black box approach. Other possibilities are to look into strategies to improve the plants' uptake of Fe, e.g. through excretion of phytosiderophores, acids or other chelates, or to accumulate Fe through increased translocation of Fe to the grain. Elimination of phytic acid or polyphenols for nutritional purposes apparently has trade-offs with agronomic performance. Phytic acid is needed for seed germination and establishment especially in P-deficient soils (Lott *et al.*, 2000). Polyphenols are important for resistance to predators (birds, insects) during crop growth and storage (McMillian *et al.*, 1972; Dreyer *et al.*, 1981), and for protecting the grain against moulding and pre-harvest seed germination (Harris & Burns, 1970; 1973).

Traits for a high Fe content are found in old varieties and landraces of e.g. wheat but not in modern varieties, which raises the question whether breeding for higher yields was at the same time accompanied by a lower Fe content (Graham *et al.*, 1999). There seems to be a growth penalty on the accumulation of Fe because of associated high energy (NADPH) consumption (Schachtman & Barker, 1999). Another explanation for decreasing Fe content in high yielding varieties may be a dilution effect due to increasing grain masses.

Literature and the sorghum screening experiment showed that there is scope for breeding to increase Fe content and decrease the phytic acid-Fe molar ratio. Breeding for zero phytic acid or zero tannins, supposedly having negative agronomic side-effects, is not necessary. Within the programme, experimental work has started on gathering information on the exact physiological pathways and roles of anti-nutritional factors, Fe and Zn in the plant. The experiments include measuring and observing phenological characteristics of existing varieties. Modern molecular techniques such as amplified fragment-length polymorphism (AFLP) analysis and specific molecular statistics will be used to link the Fe, Zn and phytic acid contents of the grain to the uptake, transport and translocation processes and to the potentially responsible genes. Further experiments will verify the resulting linkages. Fieldwork is being performed to verify agronomic trade-offs in yield or resistance to birds and insects. The work is done on millet in parallel with sorghum, developing an efficient integrated breeding strategy aiming at high Fe and Zn and low phytic acid contents in both crops. So far only preliminary results have been obtained, not allowing for any reporting at this stage.

Processing and preparation

Above it was shown that is possible to produce sorghum grain varying in Fe content and phytic acid-Fe molar ratio. The effect of processing these grains is related to the distribution of micronutrients and anti-nutritional factors over the grain and the form in which the micronutrients are present. Hubbard *et al.* (1950) analysed dry matter fractions of five sorghum varieties and found that the germ accounts for 70%, the bran for 10% and the endosperm for 20% of the ash fraction (including Fe).

Milling

Fe, phytic acid and tannin are not evenly distributed over sorghum grains. So removing the outer layer by milling or pearling affects their relative proportions in the end product. Pedersen & Eggum (1983) showed that milling decreased the contents of phytic acid and tannins but also that of Fe. Rao & Deosthale (1980) reported that pearling led to losses of Fe and P but increased ionizable Fe as a result of removing part of the anti-nutritional factors responsible for the low bioavailability of Fe from the whole grain. Salunkhe *et al.* (1982) confirmed that tannins are mainly located in the seed coats and in the pericarp of sorghum grains. Doherty *et al.* (1982a; b) found the bran-aleuron layer of sorghum grains to be the reservoir of phytic acid and total P. Dehulling was found to remove large amounts of both phytic acid and total P. The strong relationship between total P and phytic acid-P makes it unlikely that any attempt to increase the fraction of non-phytic acid-P by increasing total P will meet with success. The phytic acid-P fraction in sorghum grain varied between 73 and 90% of total P, depending on variety.

Soaking and germination, and fermentation

Soaking activates phytase, reducing phytic acid. So traditional milling, which includes soaking prior to milling, leads to lower phytic acid and higher bioavailable Fe contents of sorghum flour (Mbofung & Ndjouenkeu, 1990). Depending on temperature and duration, soaking with distilled water or sodium hydroxide also reduces tannins in sorghum flour (Chavan *et al.*, 1979; Price *et al.*, 1979). Chavan *et al.* (1981) showed that germination at 30 °C in moist conditions reduced tannin in low and high tannin sorghum varieties, depending on duration of the treatment.

Fermentation is known to have beneficial effects on bioavailability of metal micronutrients by degrading polyphenols or by hydrolyzing phytic acid into lower inositol phosphates that have less power to bind the metal ions. Together with soaking and germination, fermentation creates the optimum pH conditions for endogenous phytase in cereals, leading to an increase in soluble Fe. Svanberg *et al.* (1993) showed that soluble Fe in sorghum and maize gruels prepared without soaking increased from about 5% in non-fermented to around 10% in fermented gruel. Prepared with soaking, soluble Fe increased up to 40% and in some cases even to 50%, while at the same time the phytic acid content decreased from 14 μmol g^{-1} to 0 μmol g^{-1}.

Nout & Sarkar (1999), working with many traditionally lactic acid fermented foods in tropical climates, showed the potential of increasing Fe bioavailability in locally processed foods from different origins. They present examples of lactic acid fermentation degrading phytic acid and polyphenols in different cereal flours and of directly increasing *in vitro* Fe solubility in low and high tannin sorghum.

Processing towards specific products

Making sorghum-based products can have unexpected results on Fe bioavailability. During the making of tortilla, phytic acid-P appeared to be concentrated in the product whereas non-phytic acid P disappeared during the cooking/steeping process (Doherty, 1982a; b). Producing sorghum gruel, using increasing percentages of peanut paste increased the Fe content (source: peanut butter) but also increased phytic acid and fibre contents (neutral detergent fibre), which led to a lower soluble and ionizable Fe content (Mbofung & Ndjouenkeu, 1990). During the making of sorghum beer, soaking, germination and fermentation take place. As a result sorghum beer with various amounts of suspended solids is produced. The beer with the highest solids showed the highest mineral and trace element contents but no detectable phytic acid, implying that the elements present should be biologically available to the consumer (Van Heerden *et al.*, 1987).

The literature research showed that several processing steps influenced Fe, tannin and phytic acid contents and thus the supply of bioavailable Fe from sorghum-based products. However, the effect of processing is related to the initial quality of the raw material, the sorghum grain, which depends on variety and growing conditions. Within the programme this led to the following research question(s):

1. Which sorghum-based products are most promising for supplying (micro)nutrients to the consumer?
2. Which unit operations in sorghum-based food can be used to increase the supply of bioavailable Fe?
3. Which factors determine the farmers'/ processors' choice of sorghum varieties?
4. How well suitable are specific varieties for the preparation of various sorghum-based products?

A first survey (Kayodé *et al.*, 2004) amongst sorghum producers, processors and consumers in northern Benin identified three categories of sorghum-based products: (1) pastes (*dibou, sifanou, foura*), (2) porridges (*koko, sorou, kamanguia*), and (3) beverages (*tchoukoutou and chakpalo*). Consumption of these products varied according to ethnicity and region. A second survey (A.P.P. Kayodé, unpublished results) revealed the different processing steps. These steps consisted of dry or wet cleaning, milling, sieving or not, cooking, blending with other substances, germination, fermentation, washing and soaking, in all sorts of combinations, depending on the desired end product. A survey amongst 180 consumers showed that foods with a high frequency of consumption include few of the beneficial unit operations (soaking, milling, fermenting, and germination) in their preparation (Table 5). *Dibou* paste is consumed as a main dish and in large quantities. Its processing includes the unit operations milling and cooking but these have limited beneficial nutritional impact. Dehulling and sieving, knowing to result in the removal of anti-nutritional factors are not included, while cooking has been reported to decrease protein digestibility (Eggum *et al.*, 1983). Moreover, many consumers (> 65%) prefer red or brown sorghum varieties (rich in tannins) for *dibou* preparation, which in combination with the mentioned unit operations leads to food that may be rich in anti-nutritional factors. Although the consumption of these foods is associated with sauces prepared from edible wild plants recognized to provide the rural diets with important micronutrients, the presence of phytic acid or tannins in staple foods such as *dibou* can seriously affect micronutrient bioavailability.

Insights from literature led to hypotheses about the impact of the found processing steps on Fe and Zn contents and their bioavailability in sorghum-based foods. Research is being continued by selecting the most promising steps and copying them in the laboratory under controlled conditions to find out whether or not the hypotheses were correct and to quantify their effects. A final step will be to optimize one or more processing steps in order to improve the supply of bioavailable micronutrients from sorghum-based foods.

To guarantee relevance of the results to the research area, an inventory was made of the produced and used sorghum varieties and the quality criteria applied to them by

Table 5. Percentage of people (n = 180) in northern Benin consuming types of sorghum food, and frequency of consumption. (Source: A.P.P. Kayodé, unpublished results).

Food type	Unit operation	Times a week sorghum food is consumed			
		4–7	2–3	1	< 1
		(%)			
Paste (*dibou*)	Milling, cooking	67	17	5	11
Porridges	Pounding, soaking, milling, sieving, fermentation, cooking	45	9	6	40
Beverages	Soaking, germination, milling, filtration, cooking, fermentation	19	8	7	66

producers and processors. Processors knew exactly which sorghum varieties were suitable for which sorghum-based products. The quality criteria per sorghum variety were not only known but also appreciated in relation to the knowledge of changing quality aspects during processing. Quality criteria were also investigated in relation to the sorghum-based foods as appreciated by the consumers. Taste and colour appeared to be dominant quality criteria in the end products, texture being an additional one for the pastes (Kayodé *et al.*, 2005). Processors and consumers did not show awareness of links between quality criteria (presence of Fe, Zn and anti-nutritional factors) and health. Genetic identification of the sorghum varieties may reveal whether certain quality criteria have a genetic basis. Any improvement in the processing steps needs to keep the quality criteria of the consumers and the genetic make up of the sorghum varieties in mind.

Discussion and conclusions

The studies presented show that anaemia and thus Fe deficiency is indeed a problem in Benin and Burkina Faso where people largely depend on sorghum for their daily meals. In Benin a diet based on a diversity of sorghum-based foods was found low in Fe and enhancers and high in phytic acid. The contribution of these foods to the supply of Fe appeared to depend on the quality of the sorghum varieties and the processing methods used. Sorghum varieties were found with high and low Fe, Zn and phytic acid contents, in different combinations, giving scope for breeding for several traits at the same time. Agronomic practices such as the application of P fertilizer and soil organic amendments aiming at increasing crop yield showed to increase phytic acid content of sorghum grain as well. This is unfortunate. Food processing experiments showed that P and phytic acid fractions are closely connected, providing only very limited room for increasing inorganic P without increasing phytic acid in the grain. Processing methods were found to comprise different unit operations, some of which decrease the content of anti-nutritional factors, but some also decrease micronutrient content. The absence of dehulling, sieving and soaking, for instance, led to high amounts of anti-nutritional factors in the local dish *dibou*.

Trade-offs between food quality and agronomic quality with respect to phytic acid and tannins leading to contradictory breeding objectives can now be dealt with by including processing, the next link in the chain. Based on the preliminary results of this study, the rational decision can be made to breed a sorghum variety with a potentially high Fe content in its grain and to add appropriate processing further in the chain to eliminate the anti-nutritional factors. Reducing phytic acid and tannins as much as possible through breeding will give a direct nutritional advantage, but close-to-zero levels are not required.

Another trade-off was shown between P fertilization for increased yield and phytic acid formation, reducing nutritional quality. However, for Zn it was shown that applying Zn fertilizer together with P fertilizer could improve the phytic acid-Zn ratio compared with the application of P fertilizer alone. Also P and Zn fertilizer increased grain yield. It will be worthwhile also to investigate for Fe which combination of micronutrient and P fertilizer leads to the highest net gain in total quantity of bioavailable micronutrients per hectare and per kg of grain.

For the moment, P fertilization to increase yield can still be recommended provided subsequent processing is such that the nutritional quality is improved by inactivating phytic acid. Adequate processing is currently being further investigated with the objective to find combinations of different unit operations leading to a high recovery of micronutrients and a high removal and/or inactivation of anti-nutritional factors. A combination of micronutrient and P fertilizer application can also be recommended as it will partly redress the unfavourable phytic acid-micronutrient ratio, while grain yields per hectare will be further increased. Further research on timing of P fertilization and interactions between P and Fe and Zn fertilizers in different soils with different organic soil amendments and under different water regimes has been carried out and will be published in the near future. Interaction with varieties is also further being investigated.

To translate the research findings into actual practices, both understanding and support are needed from the producers, processors and consumers, but also from agricultural extension and from food, nutrition and health agencies. The participatory research approach per topic already provides an interface with (a limited number of) producers, processors and consumers, exploring at the same time their interest in the problems and solutions, and including their observations and remarks. The inclusion of staff from local agricultural research entities, both in the form of PhD students doing the research and of more senior staff members for supervising these students, contributes to the institutionalization of the approach and the results of the programme and to the further dissemination and development of the technologies through their organizations.

The results can be translated into policy advice. Regional and national policies in West Africa promote soil fertility measures aimed at higher and stable yields. The results and approach of the programme can enrich their message by informing them about the possible trade-offs between yield and quality and by advising modifications in already established soil fertility measures to address quantity and quality in a comprehensive way.

Extrapolation of the scientific findings to other crops and continents is possible, but decision-making is contextual. The programme has chosen for sorghum, which can be seen as a model crop presuming that the gained insights are also valid for other crops, in particular cereal crops, although quantitative effects will certainly differ.

The programme conducts similar research in China on rice. This will enable not only a future verification of the possibilities to transfer insights to other crops, but also a comparative analysis of two types of food chains in politically and socio-economically very different contexts.

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