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REVIEW PAPER

Evaluating the production, processing and storage stages of fonio, an African grain

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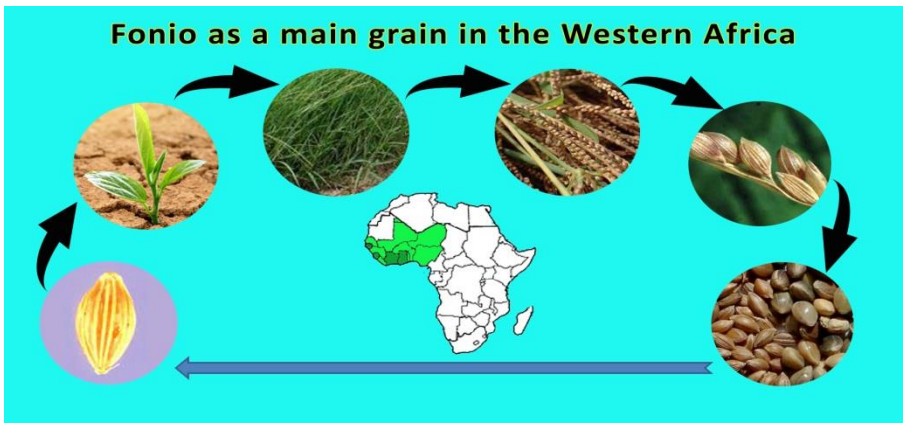
Highlights

- The stages of production, processing, and storage of fonio were studied.
- Data from projects or research programs carried out in the late 1990s.
- Fonio has long been grown as a staple food for many rural families in West Africa.
- It is well adapted to harsh weather conditions, resistant to drought, and contributes to environmental conservation.

Graphical Abstract



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Abstract

For long times, many crops have been grown to feed humans and livestock, but today only a few species are widely cultivated. Among cereals, corn, wheat, and rice are staples for many people. Some species, called rare cereals, play an important role in the food security of some of the poorest people. These crops adapted to harsh weather, resistant to drought and contribute to environmental protection by safeguarding vegetation in ecologically sensitive areas. One such crop is Fonio, a fine-grained cereal that has long been grown as a staple food for many rural families in the western Africa and is being rediscovered by urban consumers around the world. This paper introduces the mushroom crop and attempts to identify and evaluate the stages of production, processing, and storage of seeds of this African cereal and also presentation of relevant information in simple and non-technical language. Most of these data gathered from projects or research programs that began in the late 1990s, such as, "Improving Fonio Postharvest Technology", "Improving the Quality and Competitiveness of the Fonio Industry in west Africa", and "Improving the Postharvest and Development of Fonio in Africa".

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1. Introduction

Fonio is the oldest native grain of West Africa. Ibn Battuta first mentioned Fonio as a food in the mid-fourteenth century in his book Journey to Sudan. According to him, food was prepared with Fonio, the contents of which are similar to mustard seeds; He thinks rice is bad for whites, but Fonio is better. The French explorer René Kayle referred to phony in the 19th century and called it "Fiogne", meaning a small herbaceous species. In 1988, McIntosh and McIntosh, discovered that Fonio, along with rice, was their staple food, and that the emergence of certain species would improve food shortages.

In the 1950s, a famous French scientist named Roland Porters wrote an article about Fonio, citing the work of German-Dietran, a Franco-African technologist, who highlighted Fonio in the lives of financial people because it was the oldest and first cultivated seed. This grain plays an important role in other traditional African communities such as Basari in Senegal, Canyagui in Guinea or Batamariba in northern Benin.Fonio cultivation areas developed in a parallel northward direction from Senegal to Lake Chad between the 8th and 14th centuries AD, but Fonio is one of the staple foods of East Africans. Fonio is also grown in Mali, Burkina Faso, Nigeria, Benin, Senegal, and more. Outside of Africa, Fonio is also grown in the Dominican Republic. This product was imported to this country in the 15th century and is known as funde; Due to the resistance of this product to drought, farmers are interested in it. Funio seems to be rediscovering itself as a valuable product (Ezekiel et al., 2012).

2. The plant and grain

In botanical terms, Fonio is a glumaceous monocot of the grasses family (*Gramineae* or *Poaceae*) and the genus *Digitaria*. Crabgrasses, which encompass hundreds of species, are sometimes cultivated as fodder plants, and only three or four species are exploited for their grains. Hence white Fonio (*Digitaria exilis*) can be distinguished from black fonio (*Digitaria iburua*) in West Africa, hairy crabgrass (*Digitaria sanguinalis*) in Western Europe and raishan (Digitaria cruciata) in the Khasi mountains of north-east India. Today, only white fonio enjoys some degree of importance in West Africa. Its botanical name is *Digitaria exilis* (Kippist) Stapf. It is often considered to be one of the nine millet species (Stapf, 1915), and is sometimes referred to as “crabgrass millet”. English-speaking West Africa refers to it as “hungry rice” or “acha” and, locally, it is given a host of names varying between regions and ethnicities: fundi, fini, foundé, foinye, ipoaga, ova, pon, etc. In 2011, the agronomist Roland Portères, who studied vernacular generic names, concluded by saying that the terms for Fonio all has the meaning “food”, i.e. “something to eat” (Portères, 2011).

3. Herbaceous plant

Fonio is a small annual herbaceous plant 30 to 80cm in height, which has an inflorescence most often comprising two or three racemes or spikes (Fig. 1). The racemes bear spikelet's grouped in twos (early varieties), threes or fours (late varieties) on pedicels (Figs. 2 and 3). The spikelet has a sterile flower and a fertile flower which produces the Fonio grain. The stubble, cylindrical and hollow, is very fine (less than 1mm in diameter), and on maturity the stems lie on the soil. Fonio is a cereal which has good tillering (2 to 6 tillers, or more for late varieties).

The root system of Fonio is highly developed, with many fine roots and abundant lateral rooting. The particular size of this root system, which can extend down to more than one meter in depth, helps explain the good behavior of the plant during periods of drought, and its adaptation to poor soils, which it exploits efficiently. The Fonio species have great biodiversity and the many local varieties, or ecotypes, differ in color and habit of the plant, color and size of the grains, and more frequently in the length of the growth cycle (Majola et al., 2021). A distinction is commonly made between the extra-early varieties (70 to 90 days), the early varieties (90 and 110 days), semi-late (or intermediate) varieties (110 to 130 days) and late varieties (more than 130 days) vegetative growth. Collections exist for each country; one of them comprising more than 400 specimens is in France, at the Institute of Research for Development (IRD) in Montpellier (Ezekiel et al., 2012).

Fig. 1. Fonio plant (T. Meudic).

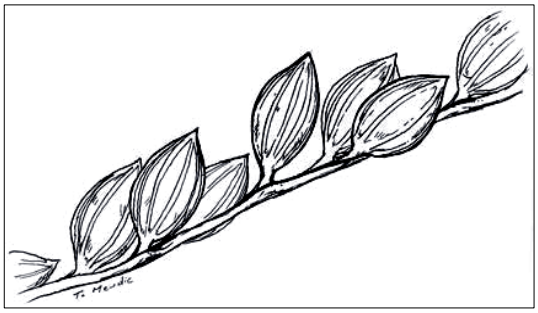

Fig. 2. Raceme portion (T. Meudic).

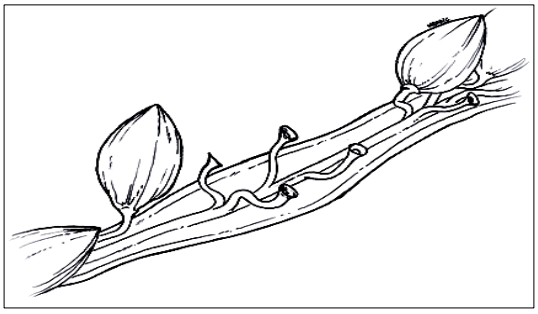

Fig. 3. Pedicels grouped in 4s (T. Meudic).

In 2011, the agronomist Roland Portères suggested a distinction into five racial groups based on morphological characteristics (Portères, 2011):

1) densa varieties: tall plants bearing 3 or 4 very long racemes (15-18cm), where the pedicels are grouped in fours (120-140 spikelets per 10cm). The grains are small and globular (2,100 grains per gram) and the plant is highly pigmented. Late varieties found in Togo under the name Semre or Sebre.
2) Rustica varieties: these are "big fonios" (foniba) bearing 2 or 3 racemes 9 to 12cm in length, where the pedicels are grouped in fours (90-120 spikelets per 10cm). Elliptical grains (1,750 to 1,800 grains per gram). Late varieties found in Guinea, Mali and Senegal under the names Foniba, Konso, Rané, Siragué, Kassambara, Tama.
3) Mixta varieties: 60cm plants with fine straw, bearing 2 or 3 racemes 8 to 12cm in length, where the pedicels are grouped in fours (90-120 spikelets per 10cm). Grains plump to ellipsoid in shape (1,900 grains per gram), with a white yellowish to pinkish pericarp. Semi-early varieties, generally coloured, found in Guinea under the names Saara, Moussogbé, Keleaningbé.
4) Stricta varieties: 40 to 65cm small plants with very fine straw, often bearing 2 racemes 8 to 12 cm in length, where the pedicels are grouped in threes (60-110 spikelets per 10cm). Ovoid, elongated grains, generally white (1,800 grains per gram) mainly over 1 row, except in the middle of the raceme. Early varieties found in Guinea, Mali and Senegal under the names Momo, Kouroukeleni, Peazo, etc. or even early white fonio.
5) Gracilis varieties: 50 to 60cm plants with fine straw, often bearing 2 racemes 8 to 14cm in length, where the pedicels are generally grouped in threes (80-90 spikelets per 10cm). Ovoid grains (1,700 grains per gram) apparently in 2 rows. Early varieties found in Guinea, Mali and Senegal under the name Berele (or Bèrèlen) (Ezekiel et al., 2012).

4. Miniscule, dressed grains

Like rice, Fonio is a so-called "dressed" cereal: after threshing, the grains retain a coating of glumes, lemma and palea, and so we talk about "paddy Fonio". This is a terminological misuse, since the term "paddy" is normally reserved for rice, referring to dressed rice grains or "rice in husk". So out of similarity and sheer

convenience, some engineers have adopted the habit of deeming non-hulled Fonio grains "paddy Fonio". These grains are very small in size, around one millimeter, and the weight of 1,000 grains is on average 0.5 g. A description of the physical and biochemical composition of the grains is given in chapter 5. Compared to other well-known cereals, Fonio grains are minuscule (Fig. 4), which makes them all the more difficult to process (hulling), and clean, since they are comparable in size to grains of sand (Ezekiel et al., 2012).

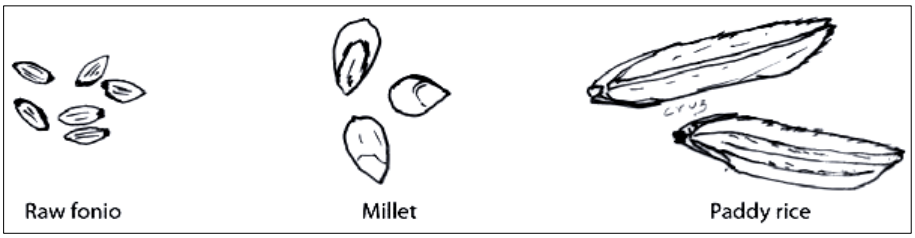

Fig. 4. Grains of "paddy Fonio" compared to millet and paddy rice.

5. Processing and grain quality

Like rice, Fonio is only consumed when hulled, and, most often, whitened. Yet in July 1827, when René Caillé described Ouassoulo in Upper Guinea, he hinted that the inhabitants consumed Fonio raw: "The country is watered by the River Sarano, and several large runoffs which fertilize the land; it produces in abundance everything that a sober man needs to live. The inhabitants are peaceful, humane, and highly hospitable […]. Their food is very simple: as in Kankan, they eat rice, tau and unground foigné; they add to this dish a sauce made with herb leaves or grilled pistaches; rarely do they employ salt, which is a luxury item, and they eat meat only on days of celebration; to their sauces, as well as gumbo, they add dried and ground baobab leaf." (Caillé, 1830). As the explorer was a fairly attentive observer, it can be assumed that the Fonio which he described was not completely whitened, but it may actually have been hulled (Ezekiel et al., 2012)

6. Fonio grain structure

6.1. Raw fonio

As already specified, Fonio is a husked cereal, whose grains, after threshing, are surrounded by "hulls" (Fig. 5). This "paddy Fonio" is not edible as-is because of the presence of these cellulose-rich hulls (glumes, lemma and palea). Raw Fonio grains have an ovoid shape, slightly flattened on the back. They are very small in size (approximately 1.8 mm in length, and 0.9 mm in width) (Ezekiel et al., 2012).

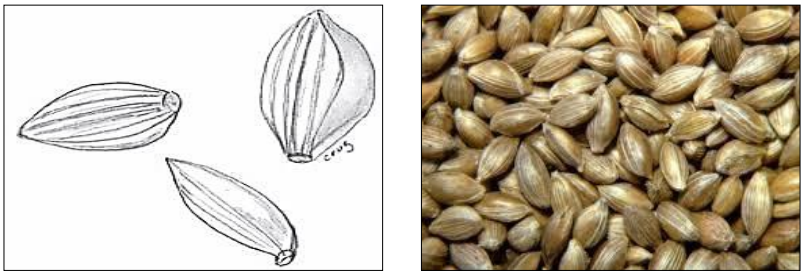

Fig. 5. Raw Fonio grains (Ezekiel et al., 2012).

6.2. Hulled or "whole" fonio

Eliminating the hulls yields a naked grain called a caryopsis. Anatomically, these hulled Fonio grains are similar to wheat, maize or millet grains, which are naked grain cereals. The hulled Fonio grain, also known as "whole Fonio", has a shiny pericarp, white to yellow to violet in color, depending on the variety. It measures just 1.4 to 1.5 mm long, 0.8 to 0.9mm wide and 0.6mm thick. On one side, the hilum can be seen (Fig. 6) and on the other, the relatively big germ, which contains the fat reserves (Ezekiel et al., 2012). The undressed grain comprises three parts: seed coat, germ and endosperm (Fig. 7).

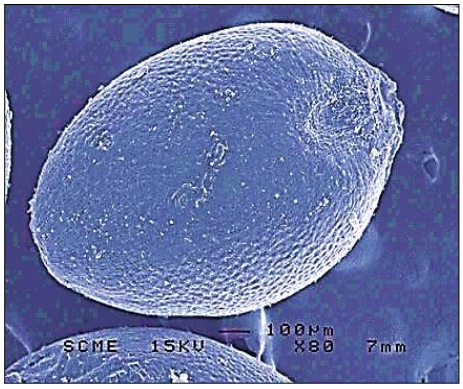

Fig. 6. Hulled fonio grain.

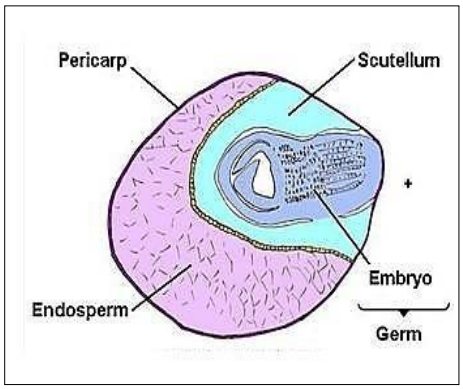

Fig. 7. Schematic cross-section of fonio caryopsis (Ezekiel et al., 2012).

The seed coat (Fig. 8) comprises:

1) The pericarp, which corresponds to the coat of the "fruit" derived from the ovary wall.
2) A proteinaceous layer or aleurone layer which represents the first layer of the endosperm. Once eliminated, the seed coat will be part of the bran, rich in cellulose and in proteins (Ezekiel et al., 2012).

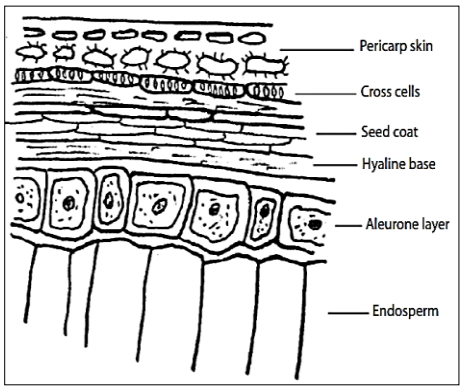

Fig. 8. Structure of fonio pericarp (Jideani, I.A., 2012).

In 2012, Jideani, described the caryopsis: "The cross-section of the caryopsis externally exhibits a row of flattened cells representing the epidermis of the pericarp (30 m in length, 6-8 m wide). Examined head on, these cells exhibit highly creased, thick walls, as we observe in nearly all the caryopses of Equatorial *Gramineae*". The germ comprises the embryo and a cotyledon (or scutellum). It represents a reserve organ, rich in proteins and fats for the young plantlet. Once eliminated, the germ will form another part of the bran, rich in fats. The endosperm represents the kernel of the grain, and corresponds to whitened Fonio. According to Jideani, (2012) the salient characteristics of Fonio caryopsis are:

1) Absence of tabular cells.
2) Irregular proteinaceous area with a single row of cells.
3) Highly developed coat, with several layers of cells.
4) Starch grains reminiscent of rice, though distinguished by their rounded, expanded hilum, which is not in a star or Y shape (Ezekiel et al., 2012). More recently, the microstructure of Fonio was studied using scanning electron microscopy (Irving and Jideani, 1997). The description is brief, but it confirms the following characteristics: the caryopsis comprises the layers of the pericarp and the testa surrounding the endosperm and embryonic tissues. The endosperm comprises a single layer of aleurone cells and starchy endosperm. The aleurone layer is thin over the whole endosperm, and thicker at the juncture between the embryo and endosperm. The aleurone cells contain droplets of fat and proteinaceous matter. The contents of the endosperm cells comprise simple polyhedral starch granules approximately 10 μm in diameter. As for rice or maize, the proteinaceous corpuscles are more abundant at the periphery of the endosperm and decrease towards the center of the grain, unlike wheat, in which the distribution is more continuous (Ezekiel et al., 2012).

6.3. Whitened fonio

Eliminating the bran (pericarp and germ) from the caryopsis yields whitened Fonio; the form in which Fonio is most often consumed (Fig. 9). On average, the whitened Fonio grain measures just 1.2 mm long, 0.7 mm wide and 0.5mm thick. The density of the whitened grains is 860 to 870 g/l (Ezekiel et al., 2012).

Fig. 9. Whitened Fonio grain.

Thus, whitened Fonio is the kernel of the grain, comprising cells filled with starch grains (Fig. 10) and a weak proteinaceous network. The microscopic appearance of starch grains differs for each species of cereals. For Fonio, the starch grains are polyhedrons, with a diameter of around ten micrometer's: 4 to 12mm (Jideani et al., 1994), 2 to 13mm (Jideani et al., 1996) or 8mm (Carcea and Acquistucci, 1997).

Fig. 10. Fonio starch grains.

7. Germination and crop maintenance

Upon the first rains, when the seeds encounter favorable temperature and moisture conditions, germination takes place quickly, within a few days. However, the rains must not be too violent, as this could shift the seeds, or bury them too deeply. By sowing on dry soil, tornadoes over the dusty soil at the beginning of the rainy season can cause the greatest damage and force the producer to re-sow his field. For germination and field emergence, a temperature of 30°C seems to be optimal. In 1988, McIntosh and McIntosh, provided the first description of Fonio germination: "In three days the cotyledon appears; the field is a dark green color (McIntosh and McIntosh, 1988). Highly drought-resistant, the young plant does not perish, although the next rain might not come for one or two weeks. The leaves curl up and dry out, but as soon as the moisture reappears, the plant starts growing again." This ability of young Fonio plants to adapt to poor soils and the random nature of the rains at the beginning of the rainy season makes Fonio one of the most resistant plants to climate change and drought. In 2011, R. Portères also described its germination and plantlet development (Portères, 2011) (Fig. 11):

1) "Fonio germinates very rapidly, and the germinating capacity is easily retained for 2 years. The radicle emerges first, and then comes the coleoptile, but the difference in growth rates is immediately such that one often gets the impression that the coleoptile emerged first. The radicle develops absorbent hairs fairly late, and does not exhibit a club shape at its end, as is generally observed in Paniceae."
2) "The pre-leaf which develops pierces the end of the coleoptile before the root undergoes ramification." "The green pre-leaf has purple borders in many breeds, is only exceptionally bronze, and is always hairy in Fonio (always hairless in Iburu); initially rolled into cornet and hooded by the coleoptile, it gradually unfurls to subsequently extend lengthwise, as in all Paniceae […]."
3) The first crown root (mesocotyl root) generally arises upon nutation of the first true leaf, when the primary root ramifies. […] Unlike what happens in Eleusine coracana, for example, the tigella does not develop quicker than the root system. Hence equilibrium is established between the organs, which helps initiate Fonio vegetation in poor and very light soils."
4) "All the leaves following the pre-leaf are tiered in the distichous position; the pre-leaf is angled 180° from the first leaf […] (Ezekiel et al., 2012).

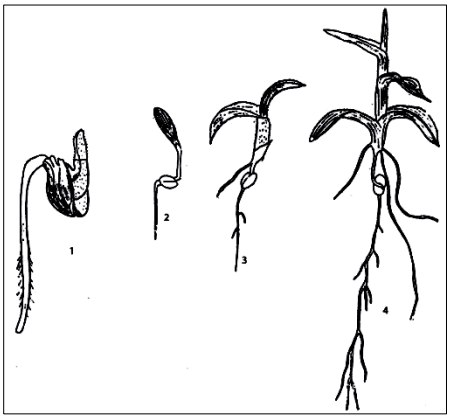

Fig. 11. Germination and development of Fonio plantlet (Portères, 2011).

At the beginning of germination, the young shoot draws much of what it needs from the seed, and then the plant becomes completely self-reliant. Like many Gramineae of tropical and arid origin, Fonio employs so-called "C4" photosynthesis, which enables a high dry matter production rate in relation to quantities of water absorbed. Photosynthesis is optimum even when the plants open their stomata only marginally, which reduces water losses via transpiration. Although Fonio is very hardy, and requires little maintenance during cultivation, it is good to eliminate the weeds to obtain a decent yield (Fogny et al., 2017). A first weeding is often carried out after four to seven weeks of vegetation. If carried out early, i.e. one to two weeks after sowing, it may significantly benefit yields at harvest, insofar as it limits competition between Fonio plants and weeds. This

weeding, which consists in manually uprooting the weeds, is a delicate operation which requires particular know-how to correctly distinguish the young Fonio shoots from the weeds. This painstaking operation is generally carried out by the women, children or the elderly, or less commonly by external labour. Weeding calls for a relatively large quantity of labour. The labour time for weeding varies from 6 man-days per hectare in semi-arid zones to 16 man-days per hectare in subhumid zones where weed growth is usually greater (Luithui et al., 2021). To separate fonio from other Gramineae, it is often necessary to wait until flowering, at which point a second weeding is essential. If, due to a lack of time or man power, weeding is not carried out, the yields are affected and the seeds collected during harvesting could be mixed up with the seeds of various weeds (Ezekiel et al., 2012).

It has already been said that Striga (*Striga hermonthica*) is one of the main enemies of Fonio growing on depleted soils. These plant parasites on many other Gramineae such as dry-land rice, maize, millet and sorghum (Ballogou et al., 2015). Weeding operations are often the only Fonio cultivation maintenance operations; which leads many producers to say that Fonio is an "easy" crop. During the vegetation process, Fonio fields will adopt various colors: dark green, and then soft green. Finally, when the grains reach maturity, the colors shift to yellow, red or brown, depending on the varieties sown and the pigmentation of the stems or spikes. McIntosh and McIntosh, (1988) spoke of a Bérélé oulé variety with very red glumes, which on maturing gives the field a rusty appearance. In cultivation, Fonio suffers little depredation, although some farmers sometimes complain of attack by certain insects (cantharid species), birds or mammals (wart hogs) (McIntosh and McIntosh, 1988). Thus Fonio may undergo a short monitoring period against birds for the first few days after sowing, or just before harvesting. Producers do not use any chemical products or input. In Middle Guinea, certain farmers who plant Fonio on the same plots every year sometimes apply NPK fertilizer, but this is relatively rare. If need be, recent research has shown that it is doubtless preferable to apply a moderate fertilizer input via a preceding crop such as legumes, or by adding manure (Gigou et al., 2009). Thus compared too many other products, Fonio, which in most regions is treated with neither fertilizer nor pesticides, has the advantage of being an "organic" crop, which can be promoted as such (Ezekiel et al., 2012).

8. Flowering and reproduction

A plant, and more specifically a variety, is characterized by the duration of its growth cycle which, divided into vegetation periods, illustrates the various stages of development. Hence several phases can be distinguished:

Installation, panicle initiation, flowering and maturation. In the Sudano Sahelian zone, many so-called traditional" cereal varieties such as millet or sorghum express photosensitivity to the length of the day, and are referred to as "photoperiodic". Depending on the variety type, the flowering date is relatively constant, regardless of the sowing-emergence date. "The plants wait to flower together." Research conducted in Mali by CIRAD and the IER (Institute for Rural Economy) demonstrated that Fonio was also a photoperiodic cereal that can regulate the duration of its vegetation phases in line with the earliness of the sowing date. Like most tropical plants, Fonio flowers mainly in the "short days." The inflorescence of Fonio was described by Portères (Portères, 2011). It most often comprises two or three racemes. The racemes bear highly interlinked spikelet's grouped in twos, threes or fours on pedicels. The spikelet with glumes has a sterile lower flower and a fertile upper flower with lemma and palea. The upper flower has three stamens with white or purple filaments and anthers which are yellow or yellow with purple pigmentation. The superior ovary has two white to pink to dark purple feathery stigmas, depending on the variety.

Many authors have long asserted that Fonio was allogamous and that it was thanks to this cross-pollination (or inter fertilization) that Fonio retained a relatively high genetic diversity (Sekloka et al., 2016). Very recently, a team of researchers from Benin and Germany showed that Fonio reproduced mainly by apomixes with little autogamy (Adoukonou-Sagbadja et al., 2007). Apomixes is a genetic particularity of certain wild plants, such as dandelion, where seeds are produced with no real fertilization (i.e. without meiosis or chromosome separation,

or fertilization or chromosome mixing). The resulting seeds are clones of the mother plant. These initial results, obtained in 2010, need to be confirmed (Ezekiel et al., 2012).

9. Genetics of fonio

The ploidy of Fonio has long remained obscure. In the 20th Century, *Digitaria exilis* was believed to have: 2n=54 chromosomes (Adoukonou-Sagbadja et al., 2006; Koreissi-Dembélé et al., 2013). Adopting a base number of chromosomes of x=9 as for other Paniceae, several authors concluded that Fonio was hexaploid, with 2n=6x=54 (Portères, 2011; Zhu, 2020). Yet some suggested that Fonio could be diploid (2n=2x=18) or tetraploid (2n=4x=36) (McWatters et al., 2003). Recent research conducted in 2006 on 94 West African varieties concluded that Fonio was tetraploid, although diploidy or hexaploidy could exist, though with a relatively low occurrence (Adoukonou-Sagbadja et al., 2007).

10. Drying the grains

Grain drying is necessary to prevent risks of alteration by mound during storage. To ensure good preservation, their water activity, or a w, must generally be less than 0.6; below this threshold, micro-organisms cannot develop and enzyme activity is prevented (Ezekiel et al., 2012). Hence the Fonio grains must be dried to a storage moisture content of 11% or less, like the sorption isotherm of Fonio shown in Fig. 12. It is interesting to note that this value is less than the value usually recommended for other cereals, under the same temperature conditions, and which is often 13%. Sun drying is commonly carried out by spreading the grains on drying areas for several days. The threshing areas or terraces of homesteads are often used to this end. Depending on the zone, mats, plastic sheets or hides may also be used. In the rainy season, natural drying cannot always correctly dry the grain from the first harvests. In certain regions of Guinea, the tradition consists in "grilling" them in a metal container placed on a hearth or heated metal plate, before hulling them for consumption. This grilling finishes the drying process by contact, which facilitates hulling (Ezekiel et al., 2012).

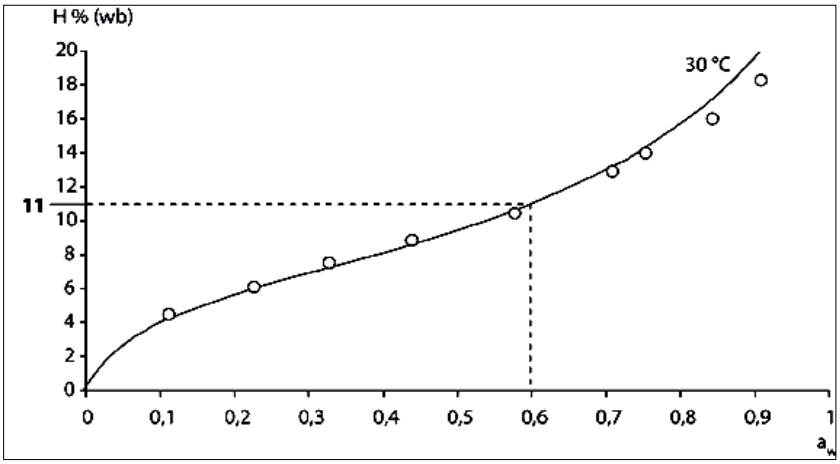

Fig. 12. Sorption isotherm of raw fonio at 30°C (Ezekiel et al., 2012).

11. Grain storage

Like rice, it is in the form of "paddy" or "dressed grain" that Fonio is usually preserved. Like other cereals, it is generally stored in bulk (Fig. 13) in traditional earth or "banco" granaries (Fig. 14). The density of raw Fonio is 650 to 660 g/l. In certain cases, it is packed into sacks, in particular when intended for sale in the form of raw Fonio or hulled Fonio. Certain producers are starting to use metal drums or plastic canisters to preserve the hulled grains. Doubtless because of its very small size, Fonio generally suffers few pest attacks during storage. If it is correctly dried to a moisture content of less than 10 or 11%, it can be kept for long months, or even years, even in traditional storage structures. As consumption needs arise, the Fonio is taken from the granaries to be

hulled and whitened before cooking. We shall now leave the domain of post-harvesting and enter that of grain processing (Ezekiel et al., 2012).

Fig. 13. Fonio stored in bulk in a traditional granary (Saidou et al., 2014).

Fig. 14. Traditional banco granaries for cereal storage (Ezekiel et al., 2012).

4. Conclusions

Our purpose in summarizing this work is to gather information about this long-overlooked African grain. Some information is very old. The implementation of several new international projects by European and African researchers and local women processors has led to the development of creative methods, especially at the post-harvest level. It is hoped that with these developments, the attention of decision-makers, especially manufacturers and other industry stakeholders, will increase. Perceptions of Fonio are changing. Formerly a rural grain and food for the poor, synonymous with famine and scarcity, Fonio attracted the attention of urban customers and was even exported. This new reputation is exaggerated in some cases, such as when certain websites and blogs call it "21st Century Grain," yet good drought resistance has made the plant fully adaptable to serious change. Fonio's nutritional properties have also made it very attractive, even though it still looks very much like rice. (Rich in amino acids and gluten-free proteins). Now, due to technological advances from research, Fonio can be found all over the world. To be offered to the people. Capable ecological assessment of planting this crop in Iran and the gradual development of commercial and organic industries can lead to high incomes for producers and farmers in different areas; however, this development must be accompanied by thinking and control to prevent Quinoa syndrome. Producing farmers should be supported because in many cases they have little technical and financial resources. The fields of genetic resources (cultivars), agriculture (sustainable production systems, ecological enhancement), post-harvest technology (washing, gravel separation, semi-cooking, packaging processes) and food science (new products) need further research. They have to meet these expectations well and Fonio will be welcomed as a genuine grain in addition to consumption in the country as a valuable export product.

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