# CHARACTERIZING FONIO PRODUCTION ACROSS SCALES: INTERDISCIPLINARY INSIGHTS FROM A LOCAL FIELD TRIAL AND A SCOPING REVIEW

By

Abigail Dingus

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## ABSTRACT

As the changing climate places new stressors on agricultural production, novel and adaptive management practices that provide resistance or resilience are needed to overcome these challenges. Increased biodiversity can improve resilience and ecosystem function, allowing agroecosystems to continue production after temporal or extreme climate events. One way to increase both local and regional diversity is by broadening the number of crops produced. Minor crops which suffer from lack of formalized research and are grown for cultural value or local adaptations, may fill niches in agroecosystems outside their traditional production systems. One of these minor crops is a small grain from West Africa called fonio. Fonio is extremely valuable in West Africa for food security, nutrition, and cultural practices, but its value has not yet been recognized globally. Increasing our understanding of this crop may provide a pathway for improving fonio for its native habitat and new environments. While there are ample uses of fonio and opportunities to improve production, there is limited research on fonio in most disciplines. This research sought to fill knowledge gaps and inform future research on fonio through two studies: a scoping review and a field study. A scoping literature review was completed where research across disciplines was summarized and analyzed for gaps in knowledge. The review found novel uses for fonio including building materials, pharmaceutical uses, industrial uses, and feed for animals. Further use of fonio is limited by knowledge gaps in the optimization of management for different environments, mechanization for production and processing, and a lack of breeding efforts. To better understand the production and uses of fonio more documentation is needed in field management, economics, seed systems, and producer/consumer preferences. A major gap identified was the viability of fonio outside its native habitat and the effect of fertilizer and seeding rate on fonio growth and forage quality. A two-year (2021-22) field study conducted in Western Michigan tested fonio production in a new environment, assessed forage quality, and determined the effect of seeding and fertilizer rate on biomass and grain yields. Results indicated that low planting densities (4 kg/ha) improved grain yields but reduced biomass. Fertilization greater than 19.5 kg N/ha increased biomass but had no effect on grain yield. Grown in Michigan, fonio forage quality was high (RFQ=131-150) when cut at booting stage but biomass yield was low compared to other summer annuals. From these studies, we determined that fonio may be a useful crop in the US as a forage or cover crop, filling a niche in perennial pastures during dry summer months. More research is needed to further understand fonio management and global uses while ensuring West African producers maintain sovereignty as the crop stewards of fonio.

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## 1. INTRODUCTION

The changing climate is increasing biotic and abiotic stress on agroecosystems. Abiotic stressors associated with climate change such as increased temperatures, temporal drought, and reduced soil carbon limit overall moisture available to plants, impacting growth and yield of crops (Aydinalp & Cresser, 2008). Increased strength of weather events is eroding soils of essential nutrients, making continuous production more difficult. More frequent flood events and rising sea levels are also damaging crops and permanently reducing usable cropland (Aydinalp & Cresser, 2008). Abiotic stressors such as increased $CO_2$, temperatures, and reduced soil fertility may also increase pressure from weeds and other pests (R. M. Adams et al., 1998). As stressors increase, agriculture production will likely decrease, causing economic loss and negatively impacting food security.

It is essential for agricultural systems to adapt or quickly recover from extreme climatic events. The ability for ecosystems to maintain organizational structure and production after a disturbance is called resiliency (Holling, 1973) and is increased by management practices such as crop diversification, use of local diversity, soil fertility management, and water conservation (Altieri et al., 2015). Increased biodiversity is an essential way to build resilient agroecosystems (Lin, 2011; Vandermeer et al., 1998) by improving ecosystem function. As functionally diverse species use different niches in the soil, available resources are more fully utilized (Lin, 2011; Song et al., 2014). Long term studies have shown that increasing plant biodiversity, specifically with functional diverse groups such as forbes, legumes, and grasses helps build soil nutrients and overall soil fertility compared to monocultures (Furey & Tilman, 2021). Efficient resource use improves ecosystem function and builds soil fertility, creating long-term resilient agroecosystems.

Closely related to resiliency is the concept of redundancy. Redundancy or insurance is when one crop fails, and others may survive to produce a crop. Increasing the number of species grown in one system can achieve this by providing a buffer from climatic variation (Lin, 2011). For example, in a warm-season intercrop study, mixtures of four species exhibited greater yield stability across environments compared to monocultures of the same species (Bybee-Finley et al., 2016). Increased number of species by crop rotations, intercropping, or integration of livestock can buffer against stressors from climate change and complete economic loss for farmers.

As abiotic stressors increase, crops are vulnerable to effects of disease and pests. Increased biodiversity may also help decrease biotic pressure from climate change. Specifically, using crops or varieties which are resistant to the pest or disease can reduce the spread and pressure (Lin, 2011; Reiss & Drinkwater, 2018). In Florida, fall army worm infestations were reduced 70-96% by changing the cover crop from a monocrop of army worm susceptible sorghum sudangrass to a mixture of sun hemp and legume cover crop (Meagher et al., 2022). In China, the fungal infection known as rice blast was reduced on the field scale and yields were maintained by intercropping varieties resistant to rice blast and lower yields with susceptible, high yielding varieties (Revilla-Molina, n.d.).

The management practice of increasing biodiversity builds resiliency, increases redundancy, and creates resistance to biotic stressors and is implemented across both temporal and spatial scales. On a temporal scale, increased number of rotations can improve yield stability. In Nebraska, diverse rotations of 2-4 years improved yield stability of corn and sorghum yields compared to less diverse rotations (Sindelar et al., 2016). The variety of crops grown in monoculture through a single year by using cover crops may also increase resilience and yields by improving soil fertility (Thapa et al., 2021). Forms of intercropping such as relay cropping, and agroforestry increase biodiversity both spatially and temporally. Spatial diversity may be improved on the field, farm, or regional scale. In the field, intercropping different species together can build resiliency and yield stability across agroecosystems (Bybee-Finley et al., 2016). At the farm level, diversity may be increased by incorporating more variety of crops, integrating livestock and pastures onto the farm, or by developing riparian zone or buffer zones. Regional diversity may also be increased using non-native crop species which are non-invasive.

The use of minor crops may be a way to protect global diversity and increase local and regional biodiversity. Minor crops are plants that are not domesticated or semi-domesticated and are used for medicines, nutrition, fuel, and other cultural practices. They are called “minor” or “neglected crops” because they have undergone “incomplete selection” or had limited formal breeding, leading to challenges such as shattering, small grain size, or lodging; or they may have other hurdles, such as processing, that require extra labor. They are often locally adapted, resistant to stressors, and maintain an abundance of new genetic material (Dansi et al., 2012; Padulosi et al., 2011). However, they are rarely utilized beyond their local context. They also are often replaced by new, higher yielding varieties of major crops, putting them at risk of genetic loss or extinction.

The use of minor crop species has benefitted U.S. agricultural systems by increasing ecosystem function, redundancy, and reducing pest pressure. For example, crabgrass (*Digitaria sanguilis*), typically considered a weed in the United States, is being grown more widely as a forage crop. The use of forage crabgrass was shown to increase the resiliency of U.S. pastures during times of drought due to increased water use efficiency compared to other perennial forages (Gelley et al., 2020). The use of the minor crops, cowpea and sun hemp as cover crops in southern Texas and Florida were shown to reduce the pressure of fall army worms (Meagher et al., 2022). Cover crop mixtures including minor crops like cowpea, sun hemp, pearl millet, and sorghum sudangrass increased yield stability across environments (Bybee-Finley et al., 2016). These studies have shown that the use of minor crops provided more biodiversity and increased resiliency in agroecosystems. A minor crop which has not yet been studied in the United States is fonio (*Digitaria exilis*), a resilient and diverse small grain crop from West Africa which may greatly contribute to the resiliency of Michigan agroecosystems as a cover, forage, or grain crop.

Fonio (Digitaria spp.) is a minor grain crop with essential uses throughout West Africa also commonly called "acha" or "fundi". In many regions, it is used for food security as quick maturing varieties fill the "hunger gap" when food stores from the previous year are low and before the major harvest (Fogny-Fanou et al., 2010a; Vall et al., 2011b). Fonio is highly adapted to low fertility soils and has high tolerance for drought. Often, it is produced at the end of many crop rotations, when the soil is exhausted (Kanlindogbe et al., 2020). Fonio is known to have a negative effect on the lifecycle of certain infectious fungus species such as charcoal-rot (*Macrophomina phaseolina*) (Ndiaye & Termorshuizen, 2008) and nematodes like root-knot worms *(Meloidogyne javanica*) (Sarr & Prot, 1985) making fonio advantageous not only for food security, but also for integrated pest management in Africa (Ndiaye & Termorshuizen, 2008). Fonio yields range between 200-1200 kg/ha and have generally increased over the last 50 years (Figure 1.1), but in most countries, total production area remains low (below 80,000 ha). The exception to this is Guinea which has higher yields and increased production area greatly in the last 50 years for unknown reasons. Depending on the region, fonio is eaten steamed like couscous and accompanied with a sauce, as a snack, as porridge for breakfast, or as baked goods, and it has the potential to be used in a large array of items such as breads or crackers (I. A. Jideani, 1999). The high protein and fiber content make it a nutritious grain for humans and livestock (C. I. Ukim et al., 2021). Fonio also has significant cultural value and is prepared for special occasions, celebrations, and ancestral worship (Adoukonou-Sagbadja et al., 2008; Ayenan et al., 2018).

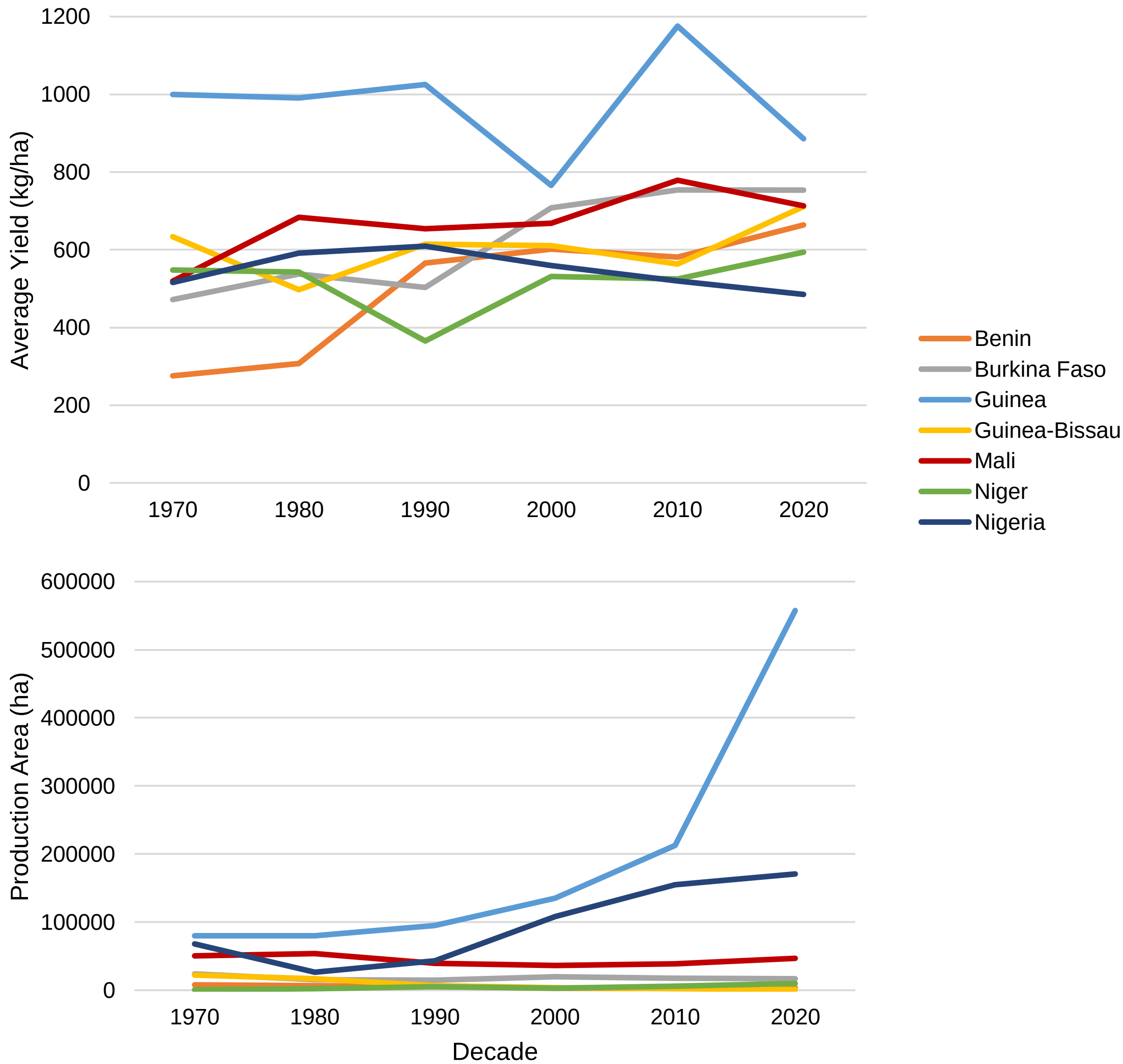


**Figure 1.1: Yield and production areas, averaged across decade, of seven major fonio producing countries in West Africa.** Data Source: FAO Stat

Fonio is one of the oldest indigenous grains in West Africa, but it is not widely known by the rest of the world and may have potential to impact several disciplines (Cruz et al., 2016). Fonio's adaptability and genetic diversity has potential to contribute to global food and nutritional security in a changing climate. Advantageous traits like drought resistance and low nutrient requirements are attributed to an extensive root system and reliance on mycorrhizal networks (Ndoye et al., 2016). Fonio may also be bred for a variety of different climates and growing conditions because of its preserved genetic diversity. For example, in Togo alone, 42 different varieties were characterized and collected from traditional farmers with varying attributes (Adoukonou-Sagbadja et al., 2008). Fonio is also considered a health food that has a low glycemic index and in gluten content while being high in essential amino acids such as lysine and methionine (Cruz et al., 2016). Thus, fonio may be advantageous for the rest of the world as a climate smart crop, as a genetic resource, or as a highly nutritious food.

Despite the many advantages to growing this crop, there are still many barriers to its production. Fonio can be variable in yield (200-1200 kg/ha) due to small grain size and grain loss (Cruz et al., 2016). Grains can be lost due to shattering (up to 30%), lodging, and postharvest processing (Ayenan et al., 2018; Cruz et al., 2016). The common weed, striga, can also cause significant yield loss (Ayenan et al., 2018; Kanlindogbe et al., 2020). Over time these barriers may continue to decrease fonio production as it is replaced by crops such as sorghum or maize that are higher yielding and require less labor (Dansi, Adoukonou-Sagbadja, & Vodouhe, 2010). In Senegal, farmers have recognized the decline in fonio production mostly due to lack of seed, tedious production practices, and disinterest of young farmers (Diop et al., 2018). The decrease in production is thus a complex social, cultural, and technological issue. With the decreased production of fonio, it may continue to be neglected by modern science unless steps are taken to preserve this valuable crop.

Because of the lack of research on fonio, there are gaps in the literature that still need to be filled and many disciplines can contribute to the optimized production of fonio. For example, engineers may be consulted for the mechanization of harvest and threshing of fonio. Studying the genetics and trait heritability may substantially improve fonio as a crop and management practices may also overcome barriers such as low yield and yield loss. For example, optimizing fertilization practices has potential to decrease pest pressure such as striga (Gigou et al., 2009; Kanlindogbe et al., 2020). It has also been found that low levels of fertilization (30 kg/ha) can increase yields by 22% and increase grain protein content (Gigou et al., 2009). With investment in crop and production methods, significant increase in yield may be achieved and costs reduced. Disciplines such as nutrition, animal science, and material science may also contribute to the development of this crop by proposing novel and profitable uses. Economists may identify optimal investment strategies to improve profitability, potentially driving research and continued production by West African farmers. Many of these disciplines have contributed to our knowledge of fonio biology, production, and uses, but there has been a lack of integration between disciplines.

Testing fonio in new environments and cropping systems such as in the United States may spread awareness about the climate smart advantages, potentially creating new markets and driving innovation. However, to our knowledge, fonio has never been grown in the United States. There is some research on production methods in West Africa, but there has never been research on how these methods may translate to new climates and cropping systems. One location that may benefit from the drought tolerance of fonio is in Michigan cropping systems. Specifically in western Michigan, the climate and the soil conditions are different from many places fonio is grown in West Africa. Michigan averages 15 ˚C night time lows, 25.5 ˚C daytime highs, and 306 mm precipitation during the growing season often with temporal drought (June-September) (*Temperature, Rainfall and Degree Day Summary - MSU - Enviroweather*, n.d.). Because of unpredictable and worsening summer drought, fonio, being a drought tolerant crop, may contribute to several Michigan agricultural systems and increase overall spatial diversity in Michigan. To test these potential niches for fonio, it must be tested in Michigan growing conditions and production practices need testing like seeding rates and fertilization strategy.

Climate change is challenging agricultural production across the globe. Increasing biodiversity and utilizing minor crops will improve the ability of agroecosystems to overcome stressors. Fonio, as a minor crop, may contribute to biodiversity in cropping systems but has been under-researched and may continue to be neglected as farmers replace fonio with major crops. Many disciplines have contributed to our knowledge of fonio but there has been lack of integration between disciplines. Thus, there are insights to be gained from mapping all research on fonio and integrating those findings across disciplines. Testing fonio in new environments and new cropping systems may also spread awareness about the climate smart advantages, but fonio production must be studied in new environments. Specifically, basic management practices such as fertilization and seeding rates are needed to start growing fonio globally. The purpose of this research is to characterize fonio production in a new environment, studying specific production parameters and mapping the extent of research that has been completed on fonio to prepare for future research.

## 2. RESEARCH QUESTIONS

Scoping Review Research Questions and Hypotheses

1. What are the existing knowledge and knowledge gaps in fonio literature in terms of its uses, production, and breeding?

2. What are specific improvements needed to optimize fonio production? What are drivers for innovation in fonio research?

We hypothesize that a scoping literature review integrated across disciplines like agronomy, economics, and plant sciences will construct a clear, informed plan to improve fonio as a crop and the technology needed to increase production. We predict that the major improvements needed will be widespread mechanization of production, breeding improvements for increased yields and processing qualities, and optimized production practices.

Field Study Research Questions and Hypotheses

1. How does fertilizer rate affect lodging, total biomass, grain yield, and plant growth characteristics?

2. How does seeding rate affect lodging, total biomass, grain yield, plant growth characteristics, and forage yield and quality?

We hypothesize that increased fertilizer will increase total biomass by increasing growth parameters such as height and number of tillers but may increase lodging and not improve overall grain yield due to plant partitioning. For seeding rate, we hypothesize that increased seeding rate will increase total biomass and grain yield but may decrease growth parameters such as plant height and tillers as competition increases. We hypothesize that seeding rate will not affect forage quality but will increase forage yield.

# 3. OPPORTUNITIES TO IMPROVE FONIO PRODUCTION: A SCOPING REVIEW TO INFORM FUTURE RESEARCH

## 3.1 Abstract

Use of minor crops can increase biodiversity, improving resiliency and stability of agroecosystems as stressors from climate change increase. Fonio (*Digitaria exilis*) is a minor grain crop in West Africa valued for its tolerance to extreme conditions like drought and poor nutrient soils and for its nutritious grains which are gluten free and high in protein. However, little formal research has been conducted on fonio. The objective of this scoping review was to summarize all electronically published research on fonio using an agroecological lens and focusing on biophysical, social, and economic elements to determine key knowledge gaps in production to direct future research. The review found numerous novel food and non-food uses for grain and waste products which may increase demand for fonio. Production of fonio is still limited with numerous knowledge gaps, particularly in the relationship of fonio response to management, genetics, and environment. Mechanization is also needed to reduce labor requirements, specifically for women. The identification of markers and study of mutagenesis in fonio lay the groundwork for breeding advancements which could increase production. Greater documentation of fonio producers' and consumers' preferences is needed to inform breeding objectives. Fonio research must increase to realize its full potential, but development of this crop must acknowledge and protect the stewardship of the West African farmers who cultivate and protect this valuable resource.

## 3.2 Introduction

Agricultural production is challenged by increased stress from climate change. Climatic events like drought and storms are worsening, causing increased pressure from pests and diseases. To overcome these challenges, agroecological management practices can help systems resist stressors or maintain production during extreme climate events or with changing temperatures. A well-researched management practice to increase resiliency, redundancy, and stability in agroecosystems is increasing biodiversity (Altieri et al., 2015; Furey & Tilman, 2021; Lin, 2011). A review of 172 cases revealed that increased crop diversity contributed to resilience through improved ecosystem function and preservation, sustainable use of natural resources, and utilization of stress-tolerant crops (Mijatović et al., 2013). Biodiversity may be improved on multiple scales through practices such as cover cropping, intercropping, livestock integration, or increased number of rotations and crop species (Bybee-Finley & Ryan, 2018; Sindelar et al., 2016; Thapa et al., 2021). Broader use of minor crops which are non-native, non-invasive is one way to increase the total number of crops species. Minor crops are often semi-domesticated and used for medicines, nutrition, or cultural practices. While the widespread use of these crops suffers from lack of formalized research or breeding efforts to address production and/or processing challenges, they are still grown because of their cultural value or adaptations to local stressors (Dansi et al., 2012; Padulosi et al., 2011).

A minor crop with little formalized research is fonio (*Digitaria exilis*), a small grain cultivated in West Africa. Fonio increases crop diversity in West Africa since it is produced as the last crop in rotation when the soil is exhausted (Kanlindogbe et al., 2020). As a drought tolerant crop, fonio contributes to the resiliency of the food system as quick maturing varieties fill the hunger gap when food stores from the previous year are low and before the major harvest (Fogny-Fanou et al., 2010a; Vall et al., 2011b). It also provides diversity in animal feed when leftover straw is recycled to feed cattle and other animals (Cruz et al., 2016). The crop is deeply embedded in culture and food traditions as a food regularly prepared for special occasions, celebrations, and ancestral worship (Adoukonou-Sagbadja et al., 2008; Ayenan et al., 2018). Fonio is already benefitting West African farmers through traditional value, nutrients, and food security.

Globally, these agroecological advantages have not yet been recognized, but fonio, as a grain or forage crop, has enormous potential. The genetic diversity of fonio may also have global benefits for food and nutritional security. Similarly, a nutritious pseudo-grain originating from the Andes, quinoa, has an abundance of genetic diversity and is bred for different agroecosystems, with potential to increase food security globally (Bazile, Pulvento, et al., 2016; Jacobsen, 2003). In Togo alone, 42 varieties of fonio were characterized (Adoukonou-Sagbadja et al., 2008). Filling specific niches with fonio may also increase resilience of agroecosystems. For example, crabgrass (*Digitaria sanguilis*) is considered a weed in the United States but is grown as a forage crop in southern US and increases the resiliency of US pastures during times of drought due to its increased water use efficiency (Gelley et al., 2020). There is potential to find both diverse and economic uses. For example, fonio may increase global crop diversity and economic output as a second crop since there are very fast maturing varieties or as a dual use crop for both grain and forage.

While there are ample uses of fonio and opportunities to improve production, there has been limited research. The existing literature spans multiple disciplines but generally there is very little research on fonio within or across disciplines. Interdisciplinary analysis and engagement could lead to creative and viable solutions to challenges in fonio production. For example, efficiencies may be improved by consulting engineers for the mechanization of harvest and threshing of fonio, reducing labor demands on women, and increasing household capacity to produce more fonio. With improved harvesting and processing methods, a significant reduction in women’s labor and increase in yield may be achieved. Furthermore, co-creation of knowledge by understanding the nuances of farmer trait preferences in combination with studying the genetics and trait heritability may substantially improve fonio as a crop. Additional insights may be found through interdisciplinary engagement to assess if genotype by environment by management influences the nutrient quality of end-products for both humans and livestock. Disciplines such as nutrition, animal science, and material science may also contribute to the development of this crop by proposing novel and profitable uses. Many disciplines contribute to our knowledge of fonio but there is a lack of integration between disciplines. We propose to examine these gaps through a scoping review to gain insights from the integration of research across disciplines.

Scoping reviews are often used to identify gaps in knowledge across a broad range of disciplines (Arksey & O'Malley, 2005). These reviews are common in the health sciences where a vast amount of research must be synthesized to find gaps in knowledge (Tricco et al., 2018). In the case of fonio, there is very little primary research, and it is spread across many disciplines. Several systematic reviews have been done within disciplines such as nutrition (Kanupriya & Dhiman, 2021; Salahudeen & Orhevba, 2021), food science (Zhu, 2020), breeding (Abdul & Jideani, 2019), and genetics (Ayenan et al., 2018). There are no known reviews for agronomy, animal science, engineering, or plant physiology, or across disciplines. Here, we use a scoping review to map the areas of fonio research which have been studied, highlight knowledge gaps and opportunities related to fonio production, and analyze how production may be impacted by multiple disciplines (Arksey & O'Malley, 2005; Tricco et al., 2018). The objectives of this scoping review are to:

1. Build a database and summarize all published research on fonio
2. Identify knowledge gaps in fonio production
3. Analyze how multiple disciplines may inform production knowledge gaps

This research is needed to better inform breeders, engineers, and farmers. Learning from other disciplines and crops may prevent harming the traditional farmers like in the case of quinoa (Drew et al., 2017) or technology that is unlikely to be adopted like in the case of sorghum breeding (Diallo et al., 2018). A cross-disciplinary literature review of fonio will increase our knowledge about fonio and provide insights for future research.

## 3.3 Theoretic Framework

An agroecological lens was used to analyze key disciplines related to fonio production. Agroecology has ten elements summarized by the FAO's publication, *The 10 Elements of Agroecology* (FAO, 2018), and include: diversity, co-creation of knowledge, synergies, efficiency, recycling, resilience, human and social value, culture and food traditions, responsible governance, and circular and solidarity economy. This theory integrates elements from multiple disciplines, specifically agronomy, ecology, sociology, and economics and is widely accepted framework for interdisciplinary analysis of agricultural systems (Dalgaard et al., 2003). Scoping and reviewing literature on fonio production benefits from this framework by going beyond biophysical systems to the social and economic aspects of crop research and breeding. Specific aspects of the agroecological framework like soil health, animal health, biodiversity, social value, and food traditions, were directly summarized as related to fonio in specific disciplines. We also emphasize specific topics which would benefit from co-creation of knowledge such as breeding objectives and development of an equitable seed system.

To guide our analysis from the generation of specific, basic knowledge and the application of that knowledge, we simplified the ten elements into three broad categories. Three overlapping areas were the biophysical, social, and economic aspects of each topic (Figure 3.1). We used these categories to evaluate what basic knowledge exists and how it may be applied with potential effects on social and economic aspects. For example, there are proposed uses for fonio and the physical attributes of fonio have been studied to allow for these uses, but there are unknowns on the application such as: How do the fonio products compare economically to the original product and how may the new uses for fonio affect the producers? Also are the new products acceptable to consumers and how has adoption of fonio changed over time? These proposed applications for fonio may then direct breeding programs and other biophysical research.

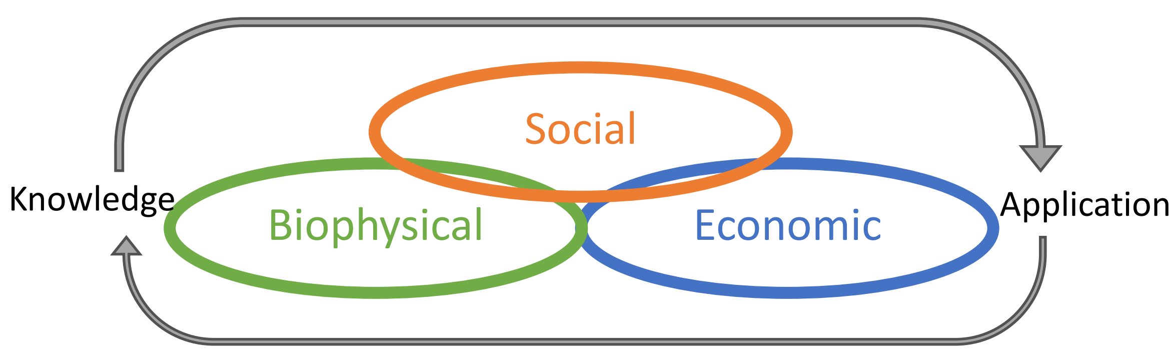


**Figure 3.1: Graphical depiction of the framework used to analyze each topic area for research gaps moving from basic knowledge to application of knowledge.**

## 3.4 Methods

A scoping review of literature on fonio was conducted across disciplines to map existing literature, identify key knowledge gaps, and integrate those findings. The methodological framework proposed by Arksey & O'Malley (2005) was used by including the five stages the authors identify for conducting a scoping literature review: identify the research question, identify relevant studies, study selection, chart the data, and summarize and report the results (Figure 3.2). The 20 elements for a scoping review created by Tricco et al. (2018) were also included. As with many scoping reviews, our purpose was to review and synthesize across disciplines rather than evaluate the scientific quality of each study included (Arksey & O'Malley, 2005). A broad research question was identified: what is known from the existing literature about fonio; its biology, production, and uses? The parameters of study were further defined by narrowing the review to true fonio (*digitaria exilis)*. A similarly related species called black fonio (*digitaria iburu)*, is often included and compared in research on true fonio. Iburu or black fonio was included in the study, but not specifically searched for. Other crab grass species (*Digitaria spp.*), and animal or wild fonio (*Brachiaria deflexa*) (Lewicki, 1974) were excluded from the review. Black fonio or iburu is closely related and has similar uses to fonio but is rarely studied exclusively. *Digitaria exilis* was chosen since it is the most widespread through West Africa (Cruz et al., 2016).

To identify relevant studies, two primary search engines were used: CAB abstracts and Google Scholar. The search terms "fonio", "acha", and "*digitaria exilis*" were used in each database which yielded a total of 1,258 references, last searched on 1 June 2022. Search parameters were not limited by date to track fonio research through time. All languages were included since most fonio research from Africa is published in French. Articles were translated by google translate or found in an English version. Conference reports and abstracts were excluded because the information published in articles and conference reports/abstracts was almost always duplicated. Reference lists from extensive reviews (Cruz et al., 2016) were also searched. Only electronic published literature was included. It is possible that research not yet electronically published may have been overlooked, but due to practical constraints authors did not hand search key journals or contact relevant organizations as suggested by Arksey & O'Malley (2005). No other restrictions were utilized, but sources were sorted by date for ease of extraction.

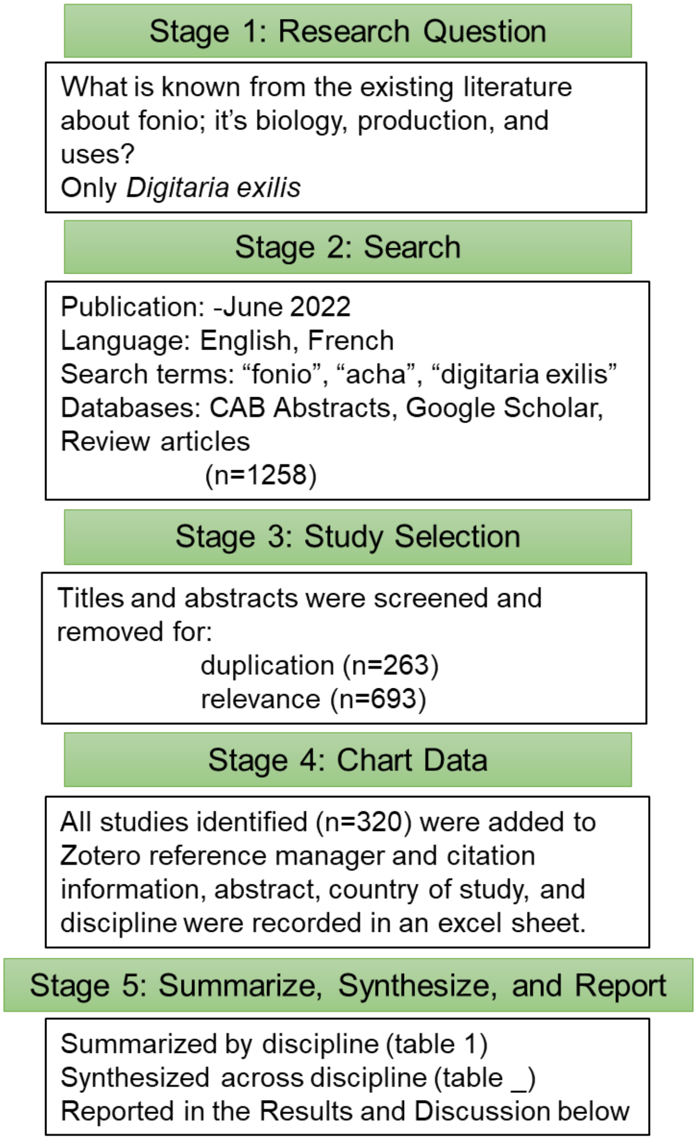


**Figure 3.2: Methodology for the scoping literature search and selection**

All references were screened by title and abstract and added to a database. Unrelated, duplicate, or conference papers were eliminated yielding a total of 320 references which were added to a Zotero reference manager. Many of the irrelevant references were related to health fields using the abbreviation "ACHA" for an organization or for the last name of an author. Articles that referenced fonio but did not do research directly related to fonio were also excluded. Next, the data were extracted and added to an excel datasheet ("charting the data" according to Arksey & O'Malley, 2005). The data included for each reference were author(s), year of publication, title, study country, discipline, subtopic, aims, methodology and important results taken directly from the abstract. Discipline criteria were based on Table 3.1. Subtopics were generated iteratively by reading abstracts in each of the disciplines and grouping similar topics together.

**Table 3.1: Description of the disciplines which the literature was sorted**

| Discipline | | Details |
|---|---|---|
| Biology | Genetics | genetics of fonio including potential genetic tools for progressing the breeding of fonio, the origins of *digitaria*, may contribute to conservation and understand diversity with implications for breeding |
| | Physiology | microscopic structure and function of fonio or its metabolic reactions, enzymes, germination, or processes and growth affecting moisture content |
| Production | Agronomy | the actual process of growing and cultivating fonio, also referring to the crop systems or distribution of fonio production |
| | Breeding | methods of breeding or information on varieties or traits |
| | Pathology | related to pests and disease that affect fonio or ways fonio is resistant or could produce a solution for pest and diseases |
| | Economics | Economic analysis of fonio production or issues of value chain |
| | Engineering | the optimization or creation of fonio mechanization for production and processing |
| Uses | Material Science | the properties of fonio incorporated building materials or properties of starch from fonio and possible food, pharmaceutical, and industrial uses |
| | Animal Science | uses as feed or fodder for animals |
| | Nutrition | nutritional benefits, chemical composition of fonio, including things mentioning the amino acid, protein, gluten content |
| | Food Science | consumption information, impact of fonio on foods, research related to starch properties, flour and flour mixture properties, or the fermenting properties of fonio grains |
| Reviews | | synthesis of information on fonio or other cereal crops, no new study or discovery, a summary of current research or findings |

After the database was created, subtopics and disciplinary findings were summarized. Each reference's abstract was read and paraphrased. Then, all paraphrases associated with the subtopic were read and a summary was written. From each subtopic in "Uses", a summary table of all potential products from fonio was created and summarized. From each subtopic in "Production", a list of major research findings and knowledge gaps were recorded. This process included a full reading and extraction of key papers to understand production practices and conditions more fully. Synergies between disciplines were then explored. For example, from engineering, it may be found that threshers often crush fonio grains and thus it is difficult to develop mechanized threshing that dehulls the grain without crushing it. This finding may influence the discipline of breeding which could select for harder grains or more easily hulled fonio grains. From each subtopic in “Biology” key findings related to fonio production or breeding were added to the above section to summarize and find key gaps in our knowledge of fonio physiology related to production.

## 3.5 Results

### 3.5.1 Research Overview

The first published record of fonio was in 1934 when it was reported as a “foodstuff” in early dietetics research (Turner, 1934). Since then, research has steadily increased and expanded to more disciplines (Figure 3.3). The topic area of “Uses” for fonio including the disciplines of Nutrition, Food Science, Animal Science, and Materials Science are the most studied areas. A total of 64% of the primary research is focused on the uses of fonio. Over time, fonio research has increased especially in categories of uses and biophysical knowledge. Research on production has continued but has not significantly grown compared to the other categories.

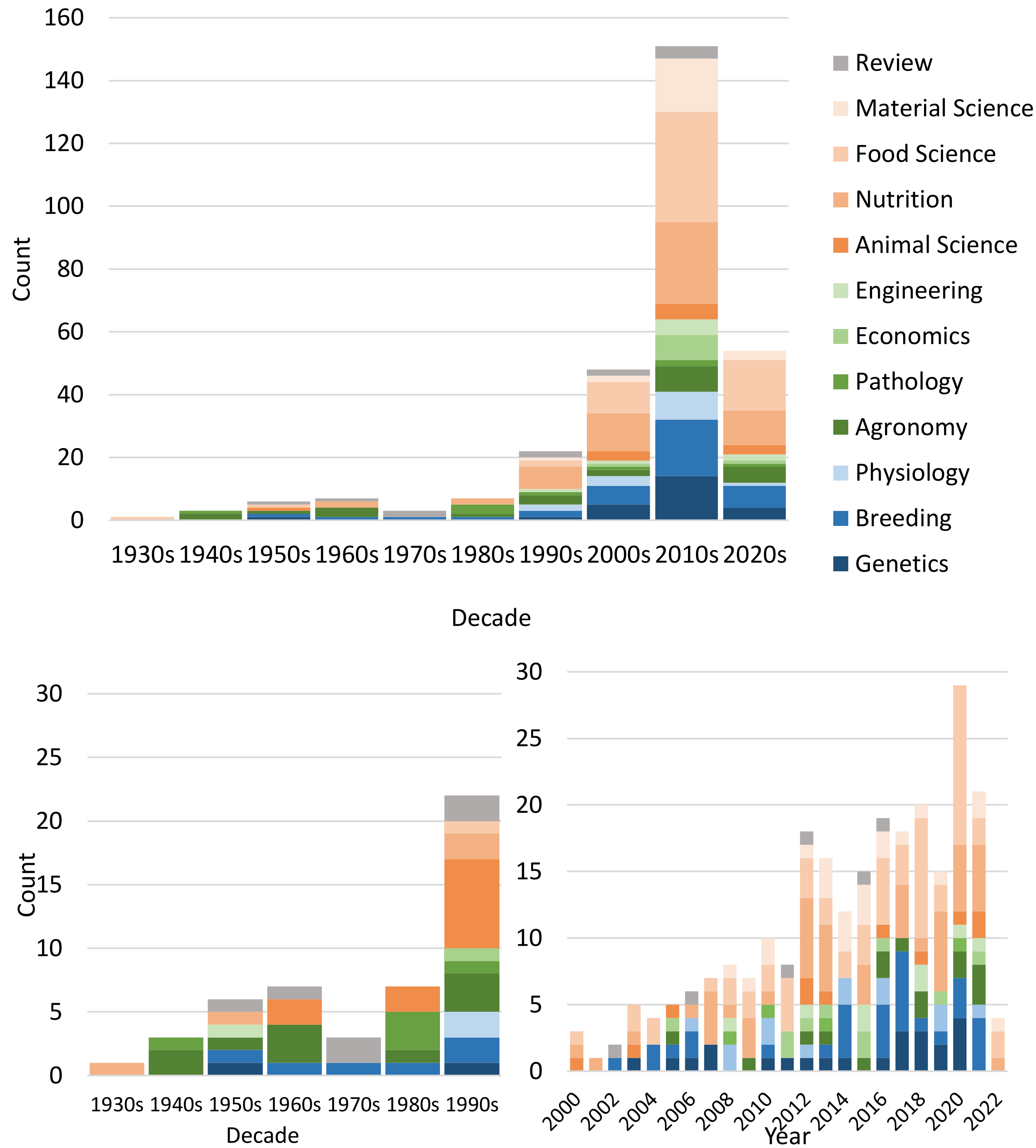


**Figure 3.3: Distribution of the references through time by discipline.** The disciplines are grouped into three topic areas indicated on the figure by color pallet: Biophysical elements (blue), Production (green), and Uses (Orange). The top graph counts the number of papers compared to decade except for the 2020's which only include data from two years. The bottom figures expand the 1900s to see specific topic breakdowns (left) and expand the 2000s by year to demonstrate the year by year growth of fonio research (right).

The earliest publications on fonio are found in descriptive studies of West African diets or farming practices (Murdock, 1960; Porters, 1955; Turner, 1934). Fonio (Digitaria exilis) has been included in many more reviews and descriptive studies since the mid-1900s mostly included as a minor crop grown in West Africa (**Supplemental Table 1**). A notable exception was a description of the history and cultivation of fonio or funde in the Dominican Republic, summarized by Morales-payán et al. (2002) where fonio is eaten as an aphrodisiac. Another key publication is: *Fonio: An African Cereal,* where Cruz et al. (2016) synthesized the distribution, production practices, and mechanization of fonio. Very few reviews have summarized original research about fonio (Abdul & Jideani, 2019; Ibrahim Bio Yerima & Achigan-Dako, 2021; I. A. Jideani & Jideani, 2011; Kanlindogbe, Sekloka, Amégnikin Zinsou, et al., 2020) and to the authors' knowledge, there have been no reviews written to synthesize research across disciplines.

### 3.5.2 Fonio Uses (Table 3.2)

*Culinary Uses*

With a nutty flavor and multiple culinary uses, fonio is eaten across different West African cultures and has potential to replace major grains. Traditionally, fonio is eaten as fluffed couscous with sauce or as nutritious porridge. These porridges are suitable as a weaning food based on the nutrient content and sensory qualities (Eboagu et al., 2020; Ugwuona et al., 2012). Foods traditionally made with maize or small grains replaced with fonio have generally high acceptability. Added to soups, fonio increased overall nutrient value of traditional foods like pumpkin soup (Helen & Ihekanu, 2009). Fonio flour can make gluten free baked goods with functional baking properties improved with the addition of 4% carboxymethylcellulose (CMC) or 3% xanthum gum (C. e. Chinma et al., 2015; V. A. Jideani et al., 2007). Mixing fonio into other flours may also increase nutrient content while preserving functional properties (Supplemental table 2). As with other small grains, fonio may be used to make traditional fermented or malted drinks but may not be economical for brewing (Nzelibe et al., 2000; Nzelibe & Nwasike, 1995). Many of these products are considered acceptable based on nutrient content and sensory characteristics like taste, texture, and smell ranked by panelists. Despite the increased research on food uses for fonio, there is little information on changing fonio consumption and perception.

Research on fonio consumption is limited but there is evidence of differences between rural and urban settings for fonio consumption. In capital cities of Mali, Burkino Faso, and

Guinea, consumer surveys representative of the population reported that the majority of people enjoyed eating fonio and wished to increase consumption (Konkobo-Yameogo et al., 2004). In another survey in urban Mali, two-thirds of women reported eating fonio monthly (Fogny-Fanou et al., 2010b). In these urban areas, fonio is valued as a health food or as a food for festivals, but consumption is limited by cost and a lack of easy-to-make fonio products like par-boiled or fully processed (Fogny-Fanou et al., 2010a; Konkobo-Yameogo et al., 2004). In rural areas of Mali, Vall et al. (2011) found through sales analysis and farmer surveys, that fonio is bought more often during lean periods and is used for seasonal food security. They found that the constraint to consumption was not cost but a lack of desire to consume fonio when other, more modern grains are available. Similarly in rural Senegal, fonio farmers most often indicated that fonio was important during food shortages (Diop et al., 2018). Unlike consumption in urban areas, fonio may be consumed in rural settings more often out of caloric need. Because of limited documentation on consumption and perception of fonio, it is unknown if these patterns between rural and urban areas are widespread across West Africa and how the perception may affect increased use or adoption of fonio products.

**Table 3.2: Uses for fonio across disciplines**

| Category | Product | Details | Citation |
|---|---|---|---|
| **Drinks** | Kunu-Zaki Drink | A drink made in Nigeria traditionally made with millets but was acceptable to a panel in aroma, taste, and nutritional qualities when made with fonio. | (J. A. Ayo, 2004; Oluwajoba et al., 2013) |
| | Malted Drink | A variety of drinks made in W. Africa from a variety of grains. Panels deemed a malted fonio drink acceptable in taste and nutritients with additives like tugernut extract. | (Abdulquadri & Rahman, 2017; Badejo et al., 2017) |
| | Fermented drink | Brewing fonio as a mixture increased the brew’s sensory qualities. Five varieties of fonio were identified to have good brewing qualities. | (Nzelibe et al., 2000; Nzelibe & Nwasike, 1995) |

**Table 3.2 (cont'd)**

| | | | |
|---|---|---|---|
| **Food** | Baby/Weaning Food | Fonio porridge as a weaning food was acceptable in nutrient quality, flavor, and color. | (Eboagu et al., 2020; Ugwuona et al., 2012) |
| | Porridge | As a breakfast food or a porridge, fonio was high in fat, protein, calcium, and was acceptable in taste. | (Henry-Unaeze, 2011; Mbaeyi-Nwaoha & Uchendu, 2016) |
| | Masa | A fermented rice cake eaten in Nigeria acceptable in nutrients and taste when rice was 20% substituted with fonio and 20% substituted with soy. | (Malomo & Abiose, 2020) |
| | Ogi and Agidi | A fermented rice or corn pudding eaten in Nigeria acceptable in nutrients and taste when grains are partially substituted with fonio. | (Chisom et al., 2020; Ogori et al., 2021) |
| | Miyan Touse or pumpkin soup | When added to a traditional Nigerian soup, fonio increases nutrients. | (Helen & Ihekanu, 2009) |
| | Flour | Fonio flours are gluten free and have higher micro-nutrients than wheat flours, and comparable functional properties with additions of 4% carboxymethylcellulose (CMC) or 3% xanthum gum. Compared to other flours like maize, rice, sorghum, and millet, fonio has higher water absorption index, swelling power, lower water solubility, and strong gel properties. | (C. e. Chinma et al., 2015; Deriu et al., 2022; V. A. Jideani et al., 2007; Onyenweaku et al., 2021) |

**Table 3.2 (cont'd)**

| | | | |
|---|---|---|---|
| | Flour additive | Fonio may also be added or combined with other flours to increase nutrient content of the flour. Many combinations have been tried with various levels of acceptability (Supplemental Table__). | |
| | Malted Flour | Malting grains increased the nutrients of the flour and functional properties but had negative effects on taste and other sensory properties according to a panel. | (J. A. Ayo et al., 2019) |
| | Oil | Fonio is low yielding for oil production but has high concentration of poly unsaturated fatty acids and Vitamins A and E. | (Ladan et al., 2018) |
| | Food Gums | Fonio starch is suitable as a gum in foods when the starch is modified by succinylation. | (Arueya & Oyewale, 2015; Olubusoye et al., 2021) |
| | Medicinal tablets | Fonio starch is suitable as an excipient for medicinal tablets. Specific modifications such as acetylation, acid hydrolysis, pregelantinized, or carboxymethylation may improve functional properties. | (Akin-Ajani et al., 2014; Emeje et al., 2012; J. K. Muazu et al., 2009; Odeku, 2013; Omoteso et al., 2019) |

**Table 3.2 (cont'd)**

| | | | |
|---|---|---|---|
| **Animal Feed** | Grain | A 100% diet of fonio grains had a positive or no effect on animal growth and nutrient use compared to a maize diet in fish, poultry, and rabbits. In egg laying hens, 12.5% of the diet may be replaced by fonio with no effect on egg production. | (Azi et al., 2021; Fagbenro et al., 2000; Nwanna et al., 2003; Oke et al., 2016; Sudik et al., 2019; C. Ukim et al., 2012; C. I. Ukim et al., 2013; Wade & Audu, 2005) |
| | Hay/Forage | Known to feed cattle. Quality or yield is unknown. | (Cruz et al., 2016) |
| | Silage | The fermentation process increases crude protein and digestibility for cattle. | (Akinfemi, 2012) |
| **Building Materials** | OPC | Fonio husk ash is an effective alternative Ordinary Portland Cement (OPC) in concrete. | (E. E. Ndububa et al., 2016) |
| | Drywall | Fonio husk combined with an adhesive liquid resin can be used as a particle board, suitable for interior wall and ceiling materials | (E. Ndububa et al., 2015) |
| **Fuel** | Briquette | Fonio husk may be turned into a briquette for use as fuel with good density characteristics and ignition, but poor burning rate. | (Bisu et al., 2017) |
| **Industry** | Enzymes for fermentation | Fonio enzymes could be used for brewing or ethanol production since the enzymatic activity was superior compared to three other microbial enzymes. | (Mulak & Ogbonna, 2015; Nzelibe et al., 2000) |

**Table 3.2 (cont'd)**

| | | | |
|---|---|---|---|
| | Silica | Fonio husk ash was found to be an efficient alternative source of silica, having higher yield and less mineral contaminants compared to rice husk. | (Shamle et al., 2014) |
| | Biodegradable packaging | Fonio starch combined with glyceral may be suitable for biodegradable packaging materials. | (Alimi et al., 2021) |
| | Other | Oxidized fonio starch may be useful as a dispersant, emulsifying agent, adhesive, disintegrants, excipients, flocculants, and other industrial uses. | (Alimi & Workneh, 2018; Isah et al., 2015) |

*Nutritional Quality*

The micro and macro nutrient content of fonio has been well studied in the last 60 years (Table 3.3) and is known to have high protein and micronutrient content (Table 3.4). Studies testing fonio-based infant food in rats showed that fonio products had higher biological value and protein efficiency ratios compared to maize products (Sudik et al., 2019). However other studies found a positive or no effect of a fonio diet on growth and development in rats (Agbede et al., 2019; Babarinde, Ebun, et al., 2020). A 10-20% fonio diet in rats also reduced blood glucose levels (Osibemhe et al., 2020) potentially due to increasing insulin secretion (D. M. Adams & Yakubu, 2020), low glycemic index (Robet et al., 2021), or alpha-amylase inhibitory activity (Okonji et al., 2014). Nutritional studies in mice show benefits of a fonio diet and consumers are known to eat fonio for its health benefits (Fogny-Fanou et al., 2010a; Kanupriya & Dhiman, 2021), but there is little research determining the benefits of fonio on human health.

Fonio grains may be processed into a gluten free flour, and nutrients may be further increased by creating flour mixtures or cooking method. Compared to common flours such as wheat and oat, fonio flour had higher concentration of micro-nutrients (Onyenweaku et al., 2021). However, like many other gluten free flours, fonio was not a source of folic acid, representing a nutrient deficiency compared to wheat flours (Jamieson et al., 2020). Fonio flour may be enhanced in protein and consumer acceptability by adding legume flour or other flours such as sesame, plantain, or carrot (Supplemental Table 2). Malting fonio grains before grinding for flour increased nutritional and functional properties, but had negative effects on taste and sensory properties (J. A. Ayo et al., 2019). Extrusion cooking improved mineral availability, protein dispersibility, and reduced antinutrients (Abiodun Victor et al., 2017; Anuonye et al., 2007; Echendu et al., 2009; Ojokoh et al., 2015). However, cooking also has the potential to decrease water soluble vitamin (Anuonye et al., 2007), phenolic, and antioxidant content (N'Dri et al., 2013). At high cooking temperatures or long cooking times, the protein availability may decrease as proteins are denatured (Chukwu, 2009). Processing and cooking methods are known to affect fonio nutrient content, and more research is needed to understand optimal methods to maintain bioavailability of nutrients.

While there are clear indications that fonio has potential as an alternative flour and has nutritional properties that would be complementary to our diets, there are many production and environmental factors that are not yet understood. For example, more research is needed on genotype by environment interactions with the nutrient content of fonio grains. In a study comparing micro and macro content across 104 samples and 3 environments in Mali, Barikmo et al. (2004, 2007) found that micronutrient content (iron, niacin, thiamine) and macronutrient content (protein, fiber, carbohydrates), was dependent on regions; suggesting that nutrient quality is not consistent across regions. Several authors (Kawuyo et al., 2019; Kayodele et al., 2019; T. K. Philip & Atiko, 2012) also found that moisture content of stored fonio grains before dehulling effects physical properties like porosity, density, seed weight, sphericity, and specific heat. It is not yet understood how moisture content may affect nutrient or antinutrient content of fonio grains. Existing research on fonio has shown it has valuable nutritional properties, but more research is needed to understand how those properties vary across varieties and environments as well as the bioavailability of the nutrients.

**Table 3.3: Count of studies analyzing fonio nutrients, sensory, and functional properties for human consumption**

| Category | Count |
|---|---|
| Major Nutrients: protein, carbohydrates, fat | 18 |
| Minor Nutrients: vitamins and minerals | 11 |
| Toxins or Anti-nutrients | 6 |
| Physical Characteristics:<br>grain size, 1000-grain weight, water absorption rate, density, porosity, specific gravity | 6 |
| Fungi or Bacteria metabolite extractions | 6 |
| Flavonoids and Volatiles | 7 |

**Table 3.4: Nutritional properties of fonio grains**

| Parameter | | Details (% per dry matter) | Citation |
|---|---|---|---|
| **Protein** | Total | 6-8% | (Barikmo et al., 2004; V. Clottey et al., 2006; De Lumen et al., 1986; de Lumen et al., 1993; Glew et al., 2013; Sadiq et al., 2015) |
| | Methionine<br>Lysine | 5-6%<br>2.6% | (De Lumen et al., 1986; de Lumen et al., 1993) |
| **Fat** | | 3-4% | (Sadiq et al., 2015) |
| **Carbohydrates** | | 74-80% | (Barikmo et al., 2004; Sadiq et al., 2015) |
| **Fatty Acids** | | 1.91% | (Glew et al., 2013) |
| **Ash** | | 2.13-2.31 % | (Sadiq et al., 2015) |
| **Amylose** | | 26.8% | (Chukwu, 2009) |
| **Fiber** | | 0.80- 2.20% | (Barikmo et al., 2004; Sadiq et al., 2015) |
| **Micronutrients** | Copper<br>Magnesium<br>Zinc<br>Calcium | 4.88 μg/g<br>1060 μg/g<br>23 μg/g<br>172 μg/g | (Glew et al., 2013) |
| | Sodium<br>Potassium<br>Iron | 0.02-0.03 μg/g<br>0.0054-0.00845 μg/g<br>0.00275-0.0011 μg/g | (Sadiq et al., 2015) |

**Table 3.4 (cont'd)**

| | | | |
|---|---|---|---|
| **Flavonoids** | | 0.039- 0.05% | (Omaji et al., 2021; Sartelet et al., 1996) |
| **Volatiles** | Identified: | Aldehydes, Heterocyclic, Alcohol, Ester, Furans, Ketone, Hydrocarbon | (Lasekan & Aina, 2003) |
| **Anti-Nutrients** | C-glycosyl flavones | Low levels | (Boncompagni et al., 2019) |
| | Tannins | Low levels | |
| | Ochratoxin A | 0.00138-0.0239 μg/g | (Makun et al., 2013) |

*Animal Uses*

Fonio grains are economical and nutritious feed for rabbits, fish, and poultry. A 100% diet of fonio grains had a positive or no effect on fish and poultry growth and nutrient use compared to a maize diet (Fagbenro et al., 2000; Nwanna et al., 2003; Wade & Audu, 2005; C. Ukim et al., 2012; C. I. Ukim et al., 2013, 2018). Female grower rabbits increased in growth when 50% of their diet was fonio (Oke et al., 2016). In egg laying hens, 12.5% of the diet replaced by fonio had no effect on egg production, and had a reduced cost in feed (Sudik et al., 2019). For both fish and poultry studies, fonio grain was determined to be more economical than maize due to increased profit indexes and less processing needed of fonio grains for feed (Nwanna et al., 2003; C. I. Ukim et al., 2018, 2021). Ukim et al. (2021) reviewed the use of fonio grain as feed for chickens and emphasized importance of fonio feed as normal feeds like maize, sorghum, and millets are more expensive in northern Nigeria after the Covid-19 pandemic. However, it is unknown the economic impact on farmers when using fonio grains as animal feed rather than for human consumption.

Fonio hay may also be used as feed for livestock as a straw, forage, or silage. It is known that fonio is used to feed animals by grazing or cutting and storing (Cruz et al., 2016). Akinfemi (2012) found that fonio straws averaged 6.28% crude protein and increased to 7.69% crude protein when fermented for silage. In vitro digestibility also improved as fonio straw was fermented for silage. Fonio may be suitable for silage and fonio straw may be improved through this process. It is unknown how fonio forage compares to other common forages in nutrients and in yield. It is also unknown if fonio is preferred by cattle. If grown as a forage crop, fonio may be used in a variety of systems like a pasture or an annual forage mixture, but it is unknown the performance of fonio in a mixture.

*Material Uses*

Fonio starch may be extracted and used in food and industrial applications (Supplemental Table 3). Fonio starches at 15% concentration increased strength by 579% compared to reference materials, making fonio starches applicable for making gluten free gel-like foods (Deriu et al., 2022). Fonio starch was found to have similar angle of repose, cars index, moisture conte, density, mean particle size to corn starch, and improved moisture sorption and swelling power compared to corn starch (Musa et al., 2008). At concentration of 2% in weight, fonio starch compares to corn starch in flow rate, flow factor, tablet properties, and may act as an alternative glidant or excipient for pharmaceutical use (J. Muazu et al., 2010). These starches combined with glycerol and made into a film was found to have applications for biodegradable packaging materials (Alimi et al., 2021). There are various uses in industry, packaging, or food industry, but the applicability of these products is still not understood. The cost of processing fonio starch has not been documented and it is unknown how fonio starch products may compare economically to non-fonio products.

Typically, fonio's husk is discarded as a waste product after the grain is cleaned, but current research demonstrates other uses for the husk. When processed into ash, the husk is an alternative raw source of silica used for a variety of application, having higher yield and less mineral contaminants compared to rice husk (Shamle et al., 2014). The husk ash may also be an effective alternative to Ordinary Portland Cement (OPC) in concrete (E. E. Ndububa et al., 2016) or combined with an adhesive liquid resin and used as drywall (E. Ndububa et al., 2015). The husk may also be turned into a briquette for use as fuel with good density characteristics and ignition, but poor burning rate (Bisu et al., 2017). These uses to recycle a waste product have not yet been economically analyzed for the financial impact to producers or the cost compared to traditional materials.

### 3.5.3 Fonio Production

*Overview*

Fonio is grown across many different environments and cultures, but production remains low with inconsistent levels of documentation. The distribution of studies in West Africa are predominately in Nigeria and Mali (Figure 3.4). Most studies have come from Nigeria, totaling 16 studies which discuss production distribution, practices, farmer demographics, and cultural perceptions of fonio. Many studies also come from Mali which detail the cultural perceptions of fonio and compare production across environments. Although it is known that fonio is produced in countries of Guinea, Burkina Faso, Ghana, and Ivory Coast, there are no documented production practices or information on fonio farmers.

Although it is grown in many different agricultural systems, the production practices remain relatively similar. As with many other crops in West Africa, fonio is produced primarily without mechanization, requiring large amounts of labor to plant, weed, harvest, and process. Labor is commonly split between men and women, with women completing the most labor-intensive tasks. Fields are prepared by animal traction or hoe and then broadcast sown. Manual weeding occurs 30-60 days after planting, primarily by women (Cruz et al., 2016; T. K. Philip & Itodo, 2012). Inputs such as herbicides, pesticides, or fertilizers are rarely used in fonio production. At harvest, men typically cut and stack sheaves to dry. Then it is threshed by walking on the grains (women) or hitting the sheaves (men) to break off the grains. The grain is gathered, sieved, and separated from the chaff by women. The process of dehulling the grain and processing it for cooking is primarily done by women through iterations of pounding with pestle and mortar and rinsing the grains (Cruz et al., 2016; Diop et al., 2018; T. K. Philip & Itodo, 2012).

As with many minor crops, women are heavily involved in the production and processing of fonio. In Nigeria, 77% of fonio production is carried out by women (Istifanus & Agbo, 2016a). In Senegal, fonio was ranked in importance by men who ranked millet, maize, and sorghum above fonio and by women who ranked fonio higher than other cereals except for sorghum (Diop et al., 2018). Processing of the fonio grain is also largely a task completed by women. In Nigeria, 90% of processing labor is completed by women (T. K. Philip & Itodo, 2012) which is a long and strenuous process. Cruz et al. (2016) reports five rounds of pounding and washing totaling 43 minutes for the entire process and with an average of 32% yield loss from start to finish, averaging 0.20 kg per hour per person. Of 16 studies on fonio production in Nigeria, only two recognize gender as a factor in production. There is potential to expand gendered research in fonio production and need for the inclusion of female voices in fonio research.

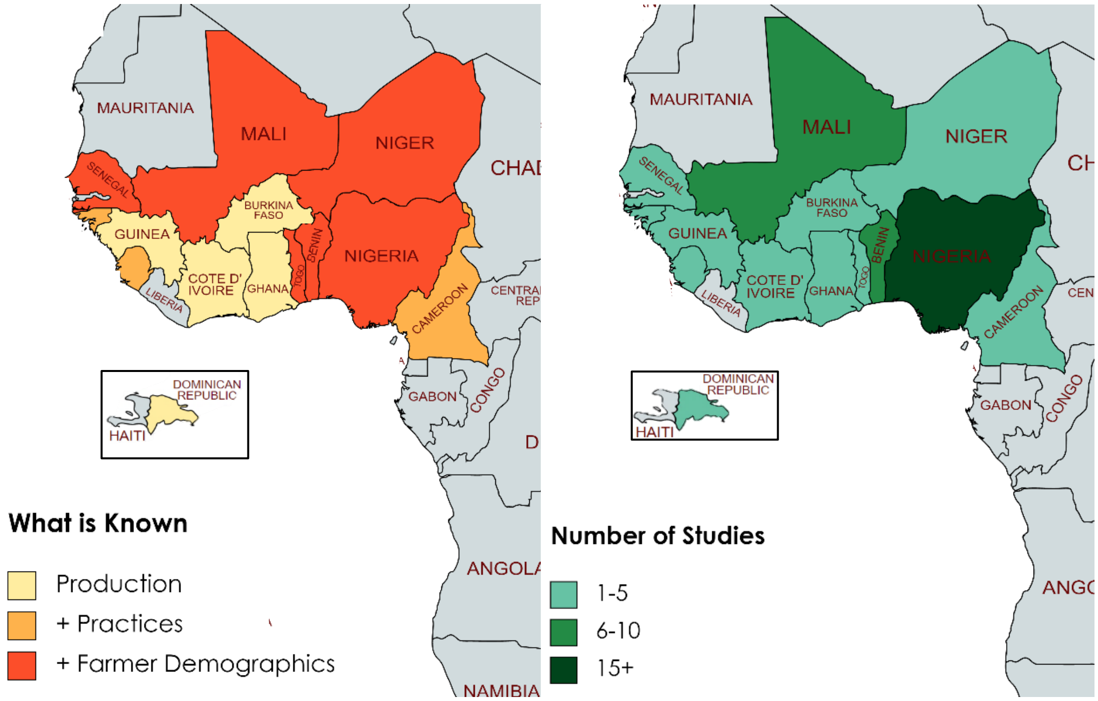


**Figure 3.4: What is known about fonio production, practices, and farmers (left) and the number of studies on these topics (right) throughout West Africa and the Dominican Republic** (Distribution of fonio production by Cruz et al., 2016 and FAO Stat)

*Constraints to production and processing*

Farmers have been surveyed in the countries of Nigeria, Senegal, Benin, Niger, and Mali to determine major constraints to production. Across regions, the major constraint to growing fonio is either low yields from small grain size or grain loss (Konate & Karambe, 2021; Popoola et al., 2020) and/or high labor intensity of weeding, harvesting, and processing fonio (Diop et al., 2018; Paraïso et al., 2016; T. K. Philip & Itodo, 2012; Sani et al., 2018) (Table 3.5). These constraints contribute to young farmers and resource-scarce farmers being less likely to grow fonio (Diop et al., 2018; Paraïso et al., 2016; T. K. Philip & Itodo, 2012; Sani et al., 2018). Diop et al., (2018) also reports that fonio production is declining due to lack of seed but does not explain the causes.

Various economic analyses provide more reasons for constraints on fonio production which follow similar trends to other crop production in West Africa. These specific economic analyses were completed in Nigeria. While findings may not be the same in other fonio producing regions, they are likely indicative of general constraints in fonio production. Similar to farmers' listed constraints, the economic analyses determine that lack of mechanization is a primary reason for inefficiency in fonio production (Kaka & Gindi, 2012). In Nigeria, in areas where fonio is grown as a cash crop, production efficiency is around 80% (Duniya, 2013, 2015; Duniya et al., 2015; Kaka & Gindi, 2012), and average profit index is 0.54 (Abdurrhman et al., 2015). Inefficiencies are also attributed to issues that affect all farming practices in West Africa such as lack of access to capital, credit, or improved seed varieties (Duniya, 2013; Duniya et al., 2015; Kaka & Gindi, 2012). The cost of transactions such as marketing or the price of seed and other inputs is another major constraint for Nigerian farmers (Duniya et al., 2015). There are many opportunities to improve fonio production.

**Table 3.5: Production constraints determined by farmers**

Constraints were determined by multiple choice surveys or open-ended question interviews. An asterisk indicates open ended questionnaires in data collection.

| Country | Constraints | Citation |
|---|---|---|
| Nigeria | Harvest and weeding were the costliest and required the most man-hours<br>Farmers most desired mechanization for dehulling and harvest | (T. K. Philip & Itodo, 2012) |
| | Lack of improved seed, mechanization, and access to credit to improve production | (Kaka & Gindi, 2012) |
| | High cost of labor for harvest and processing, high cost of fertilizer and other inputs, inadequate capital | (Duniya, 2013, 2015; Duniya et al., 2015)* |
| | Large amount of time and labor needed to weed and threshing grains, loss of grain during processing | (Popoola et al., 2020)* |
| Senegal | Decline in fonio production was attributed to lack of seed, tedious processing, and disinterest of young farmers who favor more productive crops or more profitable work | (Diop et al., 2018)* |
| Benin | High labor requirement to produce fonio lead to less young farmers or resource poor farmers not growing fonio and devoting labor to more profitable income generation | (Paraïso et al., 2016)* |
| Niger | High labor in post-harvest processing, lack of labor available since fonio harvest often coincides with major grain crops | (Sani et al., 2018)* |

**Table 3.5 (cont'd)**

| | | |
|---|---|---|
| Mali | Low grain yields (<700 kg/ha) due to lack of improved seed and optimal management | (Konate & Karambe, 2021)* |

*Seed Systems*

The seed system is an important aspect of production for sharing genetic materials and dissemination of varieties. In Benin, the fonio seed system was recorded as being entirely informal based on farmer exchange of seeds with each village, on average, maintaining one to five varieties and individual households growing one to three varieties (Dansi, Adoukonou-Sagbadja, & Vodouhe, 2010). Recording the seed system in more regions may identify weaknesses or areas that could strengthen production. For example, in Mali, seed fairs and community seed banks strengthened the seed system, increased production, and increased the number of varieties grown (Sidibé et al., 2020). Seed systems will be increasingly important as improved varieties are bred but may also benefit farmers now through access of varieties with advantageous traits. The seed system is also crucial for conservation of genetic diversity.

*Germination*

Consistent germination is an important attribute of any crop and may be improved through optimized biological and physical conditions. Hormone and photoperiod exposure were evaluated for their effect on germination. Compared to controls with no added hormones, germination rate increased with exposure to Thiourea (Idu et al., 2008) or presoaking seed in 0.2 ml Albit L-1 $H_2O$ (Anjorin & Salako, 2010). Germination decreased with exposure to 1-naphthalene acetic acid (Idu et al., 2008). Additions of Albit+superhormai resulted in more vigorous seedling growth, emergence, growth rate, and biomass compared to control with no treatment (Anjorin & Salako, 2010). The effect of photoperiod on germination and seedling development was tested with a single local variety from Nigeria. Germination rate was not affected by photoperiod, but plant growth parameters (height, number of leaves, root length) were optimal when germinated under a 12 hour photoperiod (Nyam, Angyu, et al., 2017). The studied hormone or photoperiod treatment demonstrates that fonio germination may be improved, but these studies must be expanded beyond a single variety. Other conditions for germination may also provide valuable insights for planting or preparing fonio seeds. Moisture, temperature, seed storage, and variety may play an important role in fonio germination.

*Planting*

Few studies have analyzed optimal planting methods. Traditionally, in most production zones, fonio is planted at the onset of the rainy season (Adoukonou-Sagbadja et al., 2006; Cruz et al., 2016). In southeast Senegal, an optimal planting time for early maturing varieties was before July 15$^{th}$ which increased grain yield as much as 50-87% compared to later planting dates (M. Gueye et al., 2015). More studies are needed to test optimal planting dates across agroecosystems and varieties. Other factors which may affect planting time are variety, agroecological zone, and photoperiod. While fonio is traditionally broadcast, drilling increased plant growth parameters, straw yield, and grain yield (S. Dachi et al., 2017). Drill depth was not reported but may be an important factor when planting because of small seed size. Drilling would also require technology such as a tractor and a seed drill to practically implement.

*Fertilizer*

Fonio grain yields can range from as low as 210 kg/ha to as high as 1969 kg/ha depending on production practices, varieties, and inputs. The first published research on optimizing production for fonio was published in the 1980s on the use of fodder banks to increase yields and was estimated that 40 kg/ha of nitrogen would be comparable to growing fonio in fodder banks (Tarawali, 1988). Across three agroecological zones in Mali, an observational study compared farmer practices of fertilizing and hand weeding, the highest yields (1969 kg/ha) were observed with 100 kg/ha NPK (15-15-15) fertilizer and hand weeding while the lowest yields were observed in zero input systems (Konate et al 2021). Four studies support that increased fertilizer increases fonio grain and biomass yields (Table 3.6) with the optimal range of nitrogen being between 15-30 kg/ha (Amekli, 2013; Bakare & Ochigbo, 2003; S. Dachi et al., 2017; Gigou et al., 2009). Amekli (2013) demonstrated that for three fonio landraces, the efficiency of grain production per unit of nitrogen increased and demonstrating fonio has slight response to fertilization. These studies show that fonio yields benefit from low level of fertilization, however, it is known that some fonio varieties are adapted to low fertility soils and grown at the end of many rotations (Kanlindogbe et al., 2020). More research is needed to understand the nutrient requirements of fonio and its niche in different soils across environments and varieties.

**Table 3.6: Summary and findings of fertilization studies.**

| Location | Climate | Soil Type | Treatments | Key Results | Citation |
|---|---|---|---|---|---|
| Legon-Accra, Ghana | Coastal Savanna | Ferric Acrisol | 0, 30, 60 kgNPK/ha | 30 kg/ha NPK fertilizer increased biomass and grain yield 60% of three landrace varieties | (Amekli, 2013) |
| Birnin Kebbi, Nigeria | Sudan Savanna | ferrugirious tropical | 0, 10, 20, 30, 40, 50, 60 kgN/ha | 30 kg/ha N fertilizer increased tillers, plant height, and grain yields Optimal rate of return | (Bakare & Ochigbo, 2003) |
| Birnin Kebbi, Nigeria | Sudan Savanna | ferrugirious tropical | 0, 30, 60 kgN/ha | 30 kg/ha N fertilizer increased grain and biomass yield | (S. Dachi et al., 2017) |
| Bareng & Bordo, Guinea Cinzana, Mali | Tropical, Savanna, Sahel | Ferrasol Cambisol Arenosol | 0, 15, 30 kgN/ha | 15 kgN/ha increased grain and biomass yield slightly to significantly across locations and soils. Rainfall was also a limiting factor. | (Gigou et al., 2009) |

*Drought Tolerance*

Key physical and ecological characteristics of fonio demonstrate adaptations to drought conditions. Documentation of fonio physical structure, and specifically epidermal structures have been explored through microscopy (Irving & Jideani, 1997; Okanume et al., 2014), but these structures were not related to drought tolerance until Dedeke (2021) found drought resistant varieties with specialized cells to reduce transpiration and recover from oxidative stress. Another drought resistance mechanism of fonio may be an association with microbes. Ndoye et al. (2016) analyzed fonio's response to arbuscular mycorrhizal fungi (AMF) and found fonio is dependent on certain species of AMF and plant growth increases when associated with AMF.

These are the only known drought tolerant attributes and they have only been explored in a few varieties. The metabolic, genetic, or environmental controls of these mechanisms are not well understood. To apply these findings to breeding programs, the controls for these mechanisms and the genetic markers need to be identified since not all varieties may exhibit drought tolerance.

*Pests and Pathogens*

As with many crop species, weeds, pests, and pathogens can impact fonio growth and post-harvest storage. In the field, yields may be decreased due to infection from striga (Terry, 1981) or other grass weeds (Umaru et al., 2010). These weeds are mainly controlled by hand weeding during the first month of growth (Cruz et al., 2016). Stemborers were also found to be the main insect pest of nine accessions in Nigeria along with several bird and rodent species (Umaru et al., 2010). In Niger, grasshoppers reduce fonio yields and at times, have lead to farmers abandoning fonio production (Sani et al., 2018). It is not recorded how insects, birds, and rodent pests are controlled if at all.  A leaf spot disease was identified to cause damage, and can be controlled by a fungicide (Maji & Imolehim, 2013), or genetic resistance. Three accessions (out of 23 studied) were identified to have resistance to leaf spot disease (Valerien et al., 2020). After harvest, fonio grains may be susceptible to damage from T. confusum, Aspergullus flavus, A. niger, and others with no suggested controls or prevention (M. T. Gueye & Delobel, 1999; Umaru et al., 2010). Fonio is susceptible to many pathogens but has also shown resistance and potential for use against other pathogens.

Fonio may serve a role in crop rotations to prevent or reduce the spread of disease to other crops. For example, fonio reduced the presence of tobacco leaf curl virus when planted right before tobacco (Deighton, 1940). A rotation of fonio grown in fields infected with M. phaseolina also significantly decreased infection, benefiting cowpea yields compared to other millet rotations (Ndiaye & Termorshuizen, 2008). The use of fonio in rotation for integrated pest management have been tested, but more research is needed across environments, varieties, and with other pathogens to determine the possibilities for fonio rotations.

*Harvest*

Harvesting fonio is a challenge due to shattering, lodging, and heterogeneous grain maturation. Bakare (2005) demonstrated that optimal harvest time for a single fonio variety grown in Badeggi, Nigeria was one week after physiological maturity and harvesting later increases the potential of losing grain yield to shattering. Future studies may study optimal harvest time based on variety and environmental conditions. Breeding efforts may also reduce problems with grain shattering and lodging.

*Processing*

One of the major constraints to fonio production is the amount of labor to prepare the grains for consumption, including dehulling and removing the bran. If this process were mechanized, there may be significant benefit to fonio farmers, especially women. Different researchers have evaluated modified sorghum (Marouze, 1994) and rice mills for use on fonio (Marouzé et al., 2008). Other groups have developed dehullers (Idris et al., 2018; Tokan et al., 2012) and continued to improve existing dehullers (Abdulrahman Abdulmalik et al., 2021; Ferre et al., 2018; Kaankuka, 2015). Overall, the best recorded efficiency of a fonio dehuller is 69.9% using a roller construction which increases total processing from 0.2 kg/hr by hand to 53kg/hr by machine (Abdulrahman Abdulmalik et al., 2021). This mechanization will significantly decrease the amount of time needed to process fonio. Dissemination of the technology will need careful consideration to promote equitable access and benefit all fonio farmers.

*Marketing*

If the demand for fonio products increase, understanding the market will inform production and breeding strategies. Selling strategies will benefit from documentation of consumer preferences to direct the varieties grown and how the fonio is processed for market. For example, in urban Mali, women will purchase higher quality fonio (based on color, milling, and purity) at a price premium of 1-14% (Dury & Meuriot, 2010), meaning that farmers may be able to get a higher price for certain attributes of fonio which are considered high quality. Similarly, the greatest predictor of fonio consumption in urban Mali, was attitude toward fonio (Fanou-Fogny et al., 2011) and two thirds of women surveyed had eaten fonio in the last month and a majority (95%) of women believed it was a healthy food (Fogny-Fanou et al., 2010a). Through surveys of producers and consumers, the perception of fonio has been recorded through time and across regions (Table 3.7). Generally, it is known that fonio is eaten for health, cultural, or food security reasons, but marketing strategies in specific areas would benefit from greater documentation of consumer preferences and areas with the greatest demand for fonio products.

**Table 3.7: Cultural perception of fonio through time**

| | Year | Culture | Perception | Citation |
|---|---|---|---|---|
| Consumers and Producers | Early 1900s | Fouta-Djalon, Guinea | Staple food | (Cruz et al., 2016) |
| | 1940s | Dominican Republic | Used as an aphrodisiac | (Morales-payán et al., 2002) |
| | 1959 | Mauritania | Eaten when millet was scarce | (Mazer & others, 1959) |
| | 2004 | Urban Mali, Guinea, Burkino Faso | Appreciate and want to increase consumption | (Konkobo-Yameogo et al., 2004) |
| | 2009 | Urban Mali | 2/3rds of women had eaten, and majority believed it's good for them | (Fogny-Fanou et al., 2010a) |
| | 2011 | Rural Mali | Sales increased during lean periods | (Vall et al., 2011a) |
| | 2013 | Senegal | Used in traditional medicine | (Kanupriya & Dhiman, 2021; Koroch et al., 2013) |
| | 2016 | Bauchi States, Nigeria | Farmers hold "in high esteem" | (Istifanus & Agbo, 2016a) |
| | 2018 | Senegal | Varied among ethnic groups and genders | (Diop et al., 2018) |
| Researchers | 1947 | | A secondary cereal that contributes to soil degradation | (Sudres, 1947) |
| | 1960 | | Only a staple in "backward tribes of the northern Nigerian plateau" | (Murdock, 1960) |
| | 1977 | | A minor and lesser culture cereal | (Harlan, 1977) |
| | 2006 | | A "lost crop" of Africa | (T. Philip & Itodo, 2006) |
| | 2014 | | An "economically important West African crop species" | (Mariac et al., 2014) |

### 3.5.4 Fonio Breeding

*Reproduction*

Understanding the mode of reproduction is important for breeding and improvement of crop species. Most *Digitaria* reproduce through apomixis, i.e. asexually without fertilization. Similarly, fonio reproduces by apomixis with 1.7-2% outcrossing (Adoukonou-Sagbadja et al., 2010; Barnaud et al., 2017). Because of the mode for reproduction, breeding by crossing parent materials may be more challenging, but has not been attempted.

*Genetics Tools*

In the early 1900s, study of fonio genetics was limited to observational studies and phenotypic data due to limited technology and general knowledge. As the field of genetics expanded, biotechnology has expanded our understanding of fonio. Specific genetic tools and their contribution to fonio research are outlined in table 3.8. A DNA extraction protocol and Rapidly Detecting Genomic Polymorphisms (RAPD) analyses were optimized in 2005 to inform future research (Kuta et al., 2005). SSR markers (Barnaud et al., 2012), ISSR markers (Animasaun et al., 2017), and primers (Istifanus et al., 2018; Nyam, Kwon-Ndung, et al., 2017b; Olodo et al., 2019) were identified as reference to the genome and potential site for marker assisted breeding. Chloroplast genome sequences and reference transcriptomes have also been identified for future use (Mariac et al., 2014; Sarah et al., 2017). The complete genome was sequenced by Single Molecule Real Time Sequencing (SMRT)-cell technology in 2021 (Wang et al., 2021). Many of these tools have expanded our knowledge of fonio genetics and origins but have not yet been applied in a breeding program.

**Table 3.8: List of genetic tools and uses, review studies in bold.**

| Year | Tool/Resource | Major findings | Citation |
|---|---|---|---|
| 1997 | Rapidly detecting genomic polymorphisms (RAPD) analysis | High genetic diversity of fonio with multiple domestication and/or strong agroecological differentiation | (Hitu et al., 1997) |

**Table 3.8 (cont'd)**

| | | | |
|---|---|---|---|
| 2005 | DNA extraction protocol and RAPD analysis | Optimized for future use | (Kuta et al., 2005) |
| 2007 | Flow cytometric analysis | Fonio genome size is stable across varieties | (Adoukonou-Sagbadja, Schubert, et al., 2007) |
| 2007 | Genetic distance-based clustering and principal coordinate analysis | Genetic differentiation between fonio and D. iburu, three clusters of fonio accessions related to geographical origins | (Adoukonou-Sagbadja, Wagner, et al., 2007) |
| 2012 | polymorphic simple sequence repeats (SSR) markers | Identified for future use | (Barnaud et al., 2012) |
| **2013** | **Review of advances in plant genetic research** | **Specify genetic tools for better conservation of fonio genetic resources** | (Barnaud et al., 2013) |
| 2014 | Protocol for complete chloroplast genome sequencing in fonio | Barcoded libraries were constructed for future use | (Mariac et al., 2014) |
| **2016** | **Review of genetic mechanisms of shattering** | **Summarized genetic controls of shattering and hypothesize shattering in fonio is controlled by the homologous shattering gene in rice, qSH1** | (Patterson et al., 2016) |

**Table 3.8 (cont'd)**

| | | | |
|---|---|---|---|
| 2017 | Inter-Simple Sequence Repeat (ISSR) markers | Cluster analysis of ISSR markers separated fonio and iburu into two distinct clusters with an 0.71 similarity index, they hypothesize fonio and iburu have a common ancestor but then speciated by geographical isolation | (Animasaun et al., 2017) |
| 2017 | Reference transcriptomes | Reference database for future use | (Sarah et al., 2017) |
| 2017 | Microsatellite primer combinations designed and tested | Identified distinct genetic differences between fonio and two related species | (Nyam, Kwon-Ndung, et al., 2017b) |
| 2018 | | Three primer pairs successfully separated four fonio types based on grain color | (Istifanus et al., 2018) |
| 2019 | 126 new primer pairs identified for SSR markers | Confirmed fonio is closer related to D. longiflora than D. iburu | (Olodo et al., 2019) |
| 2020 | Chromosome-scale reference assembly and re-sequencing of 183 accession of *Digitaria* | Fonio diversity is shaped by climate, geography, and ethnolinguistics<br>Genes associated with shattering and seed size show signs of domestication | (Abrouk et al., 2020) |
| 2021 | Fonio genome sequence with long-read Single Molecule Real Time Sequencing (SMRT)-cell technology | Tetraploid genome with homoeologous duplications<br>Diversity in Mali was distributed north to south along agroecosystems | (Wang et al., 2021) |

*Genetic Diversity*

Fonio has high genetic diversity primarily because of geographic differentiation. In a large study across five countries (Benin, Burkino Faso, Guinea, Mali, and Togo) and 122 varieties, three genetic groups were differentiated by geography and country of origin (Adoukonou-Sagbadja, Wagner, et al., 2007). A chromosome reference assembly created with 183 cultivated and wild varieties of *Digitaria* found that fonio diversity has been shaped by climate and geography (Abrouk et al., 2020). Sequencing of the fonio genome and further genetic analysis of varieties from Mali, also suggest genetic differentiation by geography, especially between the Sahel and grasslands of Mali (Wang et al., 2021). Fonio varietal genetics are diverse, but also stable in genome size (Adoukonou-Sagbadja, Schubert, et al., 2007). This diversity is well documented, and efforts have been made to conserve this essential resource by the assemblage of diverse genetic materials. Collections have occurred since the 1970s and have coincided with documentation of variety attributes and farmer preferences (Table 3.9).

**Table 3.9: Record of variety collections including the country, year, and data collected**

| Country | Year | # of Accessions Collected | Other Data Collected | Citation |
|---|---|---|---|---|
| Nigeria | 1971 | | Yield | (Bakhareva & Mukha, 1971) |
| Nigeria | 1995 | 138 | Farmer demographics | (Kwon-Ndung et al., 1998) |
| Ghana | 2000 | 11 | Farmer classification and selection parameters: maturity, ease of processing, storage qualities | (V. A. Clottey et al., 2006) |
| Togo | 2001 | 95 | Village ethnic group | (Adoukonou-Sagbadja, 2004) |
| Togo | 2008 | 42 | Origin, cooking qualities, growth cycle, color, size | (Adoukonou-Sagbadja et al., 2008) |

**Table 3.9 (cont'd)**

| | | | | |
|---|---|---|---|---|
| Multiple | 2013 | 20 | Sensory characteristics | (Fliedel et al., 2013) |
| Benin | 2014 | 35 | Variety names, uses, agronomic characteristics | (Ballogou et al., 2014) |
| Benin | 2016 | 20 | Maturity, yield, plant architecture, plant height | (Sekloka et al., 2016) |
| Nigeria | 2016 | 14 | Major use, qualities of farmers, farmer opinion of fonio | (Istifanus & Agbo, 2016b) |
| Nigeria | 2017 | 30 | Plant characteristics, 1000 seed weight | (Nyam, Kwon-Ndung, et al., 2017a) |
| Multiple | 2018 | 75 | Root architecture and drought tolerance | (Ogunkanmi et al., 2018) |

*Key Traits*

These varietal collections also document key traits, allowing potential breeding materials to be identified. The greatest agronomic differences between varieties were grain yield, time to maturity, plant height, and panicle or leaf characteristics (S. N. Dachi & Gana, 2021; Nyam, Angyu, et al., 2017; S. I. Saidou et al., 2014; Sekloka et al., 2016). Grain yield was found to be correlated positively to number of spikelets (A. Aliero & Morakinyo, 2002), plant height (Nyam et al., 2021), and time to maturity (Sekloka et al., 2016). Days to flowering was correlated to photoperiod and variety (A. A. Aliero & Morakinyo, 2005). Drought tolerance was also found to correlate with root architecture, specifically length of primary and lateral roots (Ogunkanmi et al., 2018). The next steps for using these traits for varietal improvement will be to identify genetic markers and controls for these traits.

*Heritability*

Very few studies have studied the heritability of agronomic fonio traits. Nyam et al. (2021) found that across 10 varieties, number of spikelets per panicle, number of tillers per plant, and 1000 seed weight had high heritability and may be used for selection to increase grain yield. The study also found that across all traits, phenotypic variance was greater than genotypic variance, indicating a strong environmental influence on variety performance (Nyam et al., 2021). In Niger, a study that evaluated 67 accessions of fonio across two environments found that differences in varietal growth parameters were greatly influenced by environment and genetic, environment interactions (S. Saidou, 2017). They suggest that in future breeding efforts, fonio must be tested across multiple environments.

*Mutagenesis*

Because of the challenge of crossing parent materials, mutagenesis may be a key method to create more genetic diversity in a breeding program. Six studies have identified methods for creating fonio mutants with improved traits either chemically, biologically, or physically (Table 3.10).

**Table 3.10: List of mutagenesis studies and their major findings, reviews in bold**

| | Tool for mutagenesis | Major findings | Citation |
|---|---|---|---|
| | **Review** | **Mutagenesis is useful for creating genetic diversity, polygenic variation, and inducing male sterility** | (Sarker et al., 1993) |
| Chemical | Nitrous acid | 4 hr of exposure to 0.1M Nitrous acid resulted in improved growth and yield of mutants | (Animasaun, Mustapha, et al., 2014) |
| | Colchicine | Produced taller, more leafy mutants with more tillers and grains per spike | (Nura et al., 2017) |
| Biological | Agrobacterium-mediated genetic transformation | Genes were successfully transferred from the agrobacterium to two varieties of fonio | (Ntui et al., 2017) |
| Physical | Gamma irradiation | 80Gy improved germination, plant growth parameters (height, tillers, leaves), early maturity, and 100 grain weight | (Animasaun, Morakinyo, et al., 2014) |
| | Gamma irradiation | 100Gy induced the most advantageous agronomic traits | (Nura et al., 2021) |
| | Alpha-spin nanoparticles | 60 min of exposure improved performance and three varieties were identified as the best performing | (Goler & Kwon-Ndung, 2020) |

*Farmer Selection Criteria*

Improvement of fonio varieties is needed especially related to agronomic characteristics. However, it is important to note that West African farmers have been selecting for specific traits for thousands of years and may provide insights to prioritize breeding objectives. Based on farmer surveys, farmers generally select based on rate of maturation, agronomic characteristics, and grain characteristics such as ease of processing, storing, cooking, color, or size (Table 3.11). The specific trait farmers select for like early maturation vs. late maturation depends on the region and the farmers' intended use for the crop. For example, in Benin, earlier maturing varieties were preferred since the crop could fill a lean period before the main harvest (Dansi, Adoukonou-Sagbadja, & Vodouhè, 2010), but in areas where fonio is produced as a cash crop, longer maturing varieties with higher grain yields may be preferred. These preferences are also gendered with women preferring varieties with an easily removed hull, good taste, or other cooking qualities. Men preferred higher yielding fonio varieties with greater drought tolerance and less lodging for ease of harvest. To ensure acceptability and adoption of improved varieties, farmers may aid in the selection process. This is also an opportunity to support women by inclusion of their preferences.

**Table 3.11: Farmer* criteria for varietal selection**

| Country | Criteria for Selection or Preference | Citation |
|---|---|---|
| Ghana | Early maturation, ease of processing (softer hull), and storage qualities (unknown specifics) | (V. A. Clottey et al., 2006) |
| Togo | Early maturation, cooking qualities, and grain lighter in color with larger in size | (Adoukonou-Sagbadja et al., 2008) |
| Benin | Early maturation, cooking qualities, ease of processing (softer hull), productivity, ease of harvest with decreased lodging, larger grain size, storage, and drought tolerance** | (Dansi, Adoukonou-Sagbadja, & Vodouhè, 2010) |
| Benin | cooking qualities, ease of processing, and agronomic traits | (Ballogou et al., 2014) |

*gender not specified

** indicated different preferences by gender

## 3.6 Discussion

As summarized above, there are many gaps in our knowledge of fonio across disciplines which may be analyzed through an agroecological framework and applied within fonio's current system as a food security crop or in new systems. Specifically, within the agroecological framework, there are key topics that can be addressed in future fonio research. Diversity may be addressed both in the functional diversity of agroecosystems and the role fonio may play in increasing functional diversity and in understanding the diverse cultural value of fonio. Efficiencies may also be improved in fonio production through breeding and mechanization and through recycling of waste products such as the husk and the stover. Across many disciplines, the recognition of human and social values will be essential to inform breeding objectives and production improvements not only across diverse cultures but also across genders and socioeconomic groups. Future research and development of new markets will rely on governance mechanisms which are "transparent, accountable, and inclusive", summarized as responsible governance (FAO, 2018).

### *Major Gaps in Current Production Systems*

Fonio is produced across West Africa, but more documentation is needed to understand the diversity of management strategies, varieties used, and cultural value of fonio. While these aspects have been recorded in a few locations (Table 3.7), our overall understanding of fonio may benefit from greater documentation. This connects back to the agroecological element of understanding the culture and food traditions of fonio, helping to honor the stewards and protect the cultural value of fonio for future generations. Similarly, there are recordings of varieties used and specific attributes that have been made in a few regions (Table 3.9), while others may still be undocumented. The current systems may benefit from wide exchange of varieties which may have advantageous traits like drought tolerance and yield. Strengthening the informal seed system for other minor crops has been shown to be effective for conservation of biodiversity and increasing food security (Gill et al., 2013). Likewise, the trade of fonio varieties with advantageous traits may enhance the ability for fonio as a food security crop and increase diversity and resiliency of these cropping systems.

Breeding is another major development that may improve food security, but better defined breeding objectives are needed with farmer preferences included. We hypothesized that breeding programs would improve production and found tools that have been developed for breeding fonio. The gap in this literature is the application and result of these tools through breeding programs. Initial breeding objectives should focus on improved agronomic aspects to increase production and decrease labor such as reduction of shattering and increased grain size. Greater documentation of consumer grain preferences and the intended culinary use (porridge, flour, or brewing) will also inform breeding objectives. Interdisciplinary teams that include breeders, agronomists and gender specialists need to document knowledge on traits for specific end-uses and environments, taking into consideration selecting for specific traits such as reduced seed shattering or larger grain may impact a desirable end-use trait (Diallo et al., 2018; Weltzien et al., 2019). This is an opportunity to create knowledge with fonio farmers that could serve to conserve traditional knowledge and genetic resources.

Another major area of improvement needed for food security is mechanization of grain processing which could increase capacity and reduce labor requirements. Women are heavily involved in fonio production, especially processing the grains for cooking, thus mechanization of processing has the potential to empower or disempower women. Mechanized tasks often become male-dominant even when the task was originally done by women (Fischer et al., 2018). Women's labor burden may be reduced by men taking over mechanized processing of grains, thus allowing for more choice in how to spend time. Increased grain processing may allow farmers to sell fonio instead of saving for home consumption. This could impact food and nutritional security since fonio is often used during lean periods and beneficial for dietary diversity (Conti et al., 2019). Increased income from fonio sales may or may not benefit women depending on the use of the income and the extent to which they have decision-making power in the use of income (Ganle et al., 2015; Mudege et al., 2015). Women and other marginalized farmers may also be further disadvantaged with a potential loss of a valuable food source if they are unable to access the mechanized technology (Eidt et al., 2020). While mechanization would substantially increase production potential, it may also become a disadvantage for traditional stewards of the crop and reduce women's control over a household food staple and nutritional security. When implementing these technologies, it will be essential to establish community groups that agree on fair and equitable use with mechanisms for resolving challenges (Fischer et al., 2018), contributing specifically to the agroecological element of responsible governance.

*Major Gaps in Knowledge of Fonio in Novel Systems*

When expanding the use of fonio in new cropping systems, a major gap in our knowledge is the effect of variety and environment on specific traits. Much of the research exploring fonio management has only been done on a single variety and environment. Thus, it is unknown if resilient traits are only present in certain varieties or environments which will become even more important if fonio production expands beyond the West African context. There is already evidence that nutrient content is dependent on variety or environment (Barikmo et al. 2004, 2007), but the effects have not been studied enough to understand the relationship between nutrition and growth environment. Further research is needed on genotype by environment (GxE) interactions and the effect on traits, yield, and nutritional quality. Globally testing varieties of quinoa helped the expansion and continued research, as its potential uses and benefits were understood (Bazile, Jacobsen, et al., 2016). Likewise, global variety testing may help expand fonio production and contribute to the resiliency of cropping systems globally.

Research is needed to identify how fonio may benefit global diversity and resilience. The greatest benefits from increased crop diversity often are from functional diversity, where different crop species use different niches and available resources are more fully utilized (Lin, 2011; Song et al., 2014). Studies have shown that increasing plant biodiversity with functional diverse groups such as forbs, legumes, and grasses help build soil fertility compared to monocultures (Furey & Tilman, 2021). However, it is not understood the specific niches that fonio uses in the soil or how it impacts microbial diversity. Likewise, it is not known how fonio may react to interspecific competition which would be important for utilizing fonio in a mixture. Fonio is also known to have reliance on microbes which aid in drought and low nutrient conditions (Ndoye et al. 2016), but it is not understood how these interactions may change as fonio is grown on different continents with potentially new microbes. To fully utilize fonio globally and improve diversity and resilience, it first must be understood how growth and adaptations translate to new cropping systems.

Research in fonio breeding and mechanization may also improve fonio production in new locations and management systems. Breeding objectives would be dependent on the intended end use of the crop as a grain, forage, or other use. Major breeding objectives for growing fonio in mechanized systems should focus on crop properties that allow mechanization such as upright growth habit, non-shattering, and higher yielding. For global production, mechanization is essential to increase production and reduce labor requirements but will require breeding programs and optimized management strategies according to the end use.

Increased global demand for fonio products may benefit or harm fonio farmers and requires responsible governance to ensure equity. Like the boom and bust trends observed in tef and quinoa (Andreotti et al., 2022), the initial increase in demand for fonio will increase production and income-generation for farmers. Research will likely improve production and potentially increase production outside of West Africa but may not benefit fonio producers in the long term. If industrialized countries or private companies take over production, then the price of fonio in West Africa may rapidly decrease and make imported fonio products cheaper than locally grown (Andreotti et al., 2022). The original growers and stewards of fonio may then be forced to buy fonio and no longer profit from fonio sales. In Ethiopia, tef exports were banned in an effort to maintain national food security and secure their genetic resources, but this was ineffective to prevent the boom and bust cycle (Crymes, 2015). There was greater success in quinoa protection in Andean countries with the creation of international research groups, farmers groups, NGOs, and the increased production of highly valued varieties that helped to maintain benefits to local producers. However, the results have varied and still result in disempowerment of some farmers who grew quinoa traditionally (Drobnack & Isaacs, in review).

Increased non-food fonio uses may further impact food security and traditional fonio uses. For example, selling crops as biofuels may improve financial security of resource-poor farmers and thus decrease vulnerability to climate and price shocks (Ewing & Msangi, 2009). There are still tradeoffs to growing crops for food versus nonfood uses. Many smallholder farmers grow crops for home consumption. Increased purchasing power may not always increase food security if the additional income is not used to purchase food. Additionally, if fonio is grown for non-food uses, then fonio processed as grain may become even more expensive, leading to less consumption of fonio and loss of cultural value (Ewing & Msangi, 2009). Therefore, great care must be taken in creation of fonio markets to support the cultural value and stewardship of fonio producers.

## 3.7 Conclusions

The scoping review sought to summarize fonio research across disciplines with an emphasis on production and the implications of research using an agroecology lens. Research on fonio has steadily increased in the last 50 years with a great emphasis on nutrients and culinary uses. Many novel uses have been identified, and to support the increased use of fonio as a food security crop or as a novel crop globally, more research is needed. Although there are many knowledge gaps, we focused on fonio production which may benefit from greater understanding of management strategies particularly across varieties and environments. Mechanization of grain processing may also increase capacity for fonio production and reduce labor requirements for women. Breeding programs would also greatly benefit fonio production by decreasing yield loss from shattering and lodging. Each of these may benefit from partnership with farmers who would provide valuable knowledge. As production and research increase, care must be given to ensure women are empowered, and producers are protected from the “boom and bust” cycle of minor crop development.

## 3.8 Supplemental Materials

**Supplemental Table 1: Descriptive summaries documenting information on fonio**

| Year | Title | Scope of Publication | Citation |
|---|---|---|---|
| 1955 | The minor cereals of the genus Digitaria in Africa and Europe | Summary of descriptive information given on D. exilis including: history, synonyms, botanical description, germination, seedling development, vernacular names, crop areas, varieties, cultural methods, harvest, yield and uses. Information is also given on D. sanguinalis and D. iburua. | (Porters, 1955) |
| 1960 | Staple subsistence crops of Africa | Summary of major crops throughout Africa. Includes the distribution of fonio in West Africa and indicates it is likely one of the oldest cultivated grains and is often replaced by sorghum and millet. Denigrates fonio as eaten only by uncivilized tribes in Nigeria | (Murdock, 1960) |
| 1974 | West African Food in the Middle Ages | Summary of many crops from Africa. Records three kinds of fonio grown in West Africa: animal fonio or guinea millet (Brachiaria deflexa), true fonio (Digitaria exilis), and black fonio (Digitaria iburu) with the distribution of each | (Lewicki, 1974) |
| 1977 | The origins of cereal agriculture in the Old World | Summary and history of cereals both major and minor cereals with fonio briefly described. | (Harlan, 1977) |
| 1996 | Lost crops of Africa: Volume 1: Grains | Summary of crop production areas and environmental requirements, uses, nutritional value, agronomy, harvesting and handling, limitations, and prospects with fonio included in one chapter | (Council & others, 1996) |

**Table 1 (cont'd)**

| | | | |
|---|---|---|---|
| 2002 | Digitaria exilis as a Crop in the Dominican Republic | Summary of fonio, called Funde, in the Dominican Republic. Brought in the early 1500s, fonio survived mostly as a weed until cultivation began in the 1940s as a grain and as a forage. | (Morales-payán et al., 2002) |
| 2006 | Acha (Digitaria spp.) a "rediscovered" indigenous crop of West Africa. | Summary of Digitaria exilis and Digitaria iburua nomenclature, history, and importance. | (T. Philip & Itodo, 2006) |
| 2012 | Digitaria exilis (acha/fonio), Digitaria iburua (iburu/fonio) and Eluesine coracana (tamba/finger millet) Non-conventional cereal grains with potentials | Summary of potential of fonio diets, wellness, economic status improvement, and role in food as a traditional food. Call for greater collaboration and development to increase the use and benefits from these crops. | (A. I. O. Jideani, 2012) |
| 2015 | Teff & Fonio – Africa's sustainable cereals | Summary of two African crops- their cultivation and uses. | (Small, 2015) |
| **2016** | Drought Adaptation in Millets | Summary of drought tolerance and strategies in several millets, including fonio. | (Tadele, 2016) |

**Table 1 (cont'd)**

| | | | |
|---|---|---|---|
| 2016 | Vernacular names for African millets and other minor cereals and their significance for agricultural history | The paper uses the patterns discerned in vernacular names to explore their history. | (Blench, 2016) |
| 2016 | Fonio, an African cereal | Summarizes the practices, yields, and culture associated with fonio cultivation. Records developments in mechanization. | (Cruz et al., 2016) |

**Supplemental Table 2: Flour blends tested for acceptability and/or benefits**

| Flour Components | Most Acceptable Composition | Benefits | Citation |
|---|---|---|---|
| Fonio, Wheat | 50:50 | Flavor, consumer acceptability Comparable to 100% wheat bread | (McWatters et al., 2003) |
| | 5:95 | Highest baking potential, dough machinability, nutritional benefits | (Drábková et al., 2017) |
| Fonio, Wheat, Cowpea, Moringa | 23:50:25:2 | Nutrients, sensory, consumer acceptability | (Orisa & Udofia, 2019) |
| Fonio, Wheat, Mungbean | 70:15:15 | Protein, fiber, minerals, fat, vitamins | (Nanyen, 2016) |

**Table 2 (cont'd)**

| | | | |
|---|---|---|---|
| Fonio, Wheat, Kidney bean | 00:75:25 or 25:50:25 | Consumer acceptability, fiber, nutritional value | (Inyang et al., 2018) |
| Fonio, Wheat, Pigeonpea | 50:20:30 | Sensory, consumer acceptability | (Adeyanju et al., 2018) |
| Fonio, Wheat, Pigeonpea | | Pasting properties, protein | (Olagunju et al., 2020) |
| Fonio, Wheat, Cashew kernel | 40:30:30 | Consumer acceptability, protein, vitamins, minerals | (Emelike et al., 2020) |
| Fonio and Bambara nut sourdough, Wheat | 10:90 | Consumer acceptability | (C. E. Chinma et al., 2016) |
| Fonio, Wheat, Amaranth | 10:70:20 | Protein, fiber, ash, lower glycemic index | (Olagunju et al., 2021) |
| Fonio, Cowpea | | Complementary proteins | (Olapade & Aworj, 2012) |
| Fonio, Cowpea, Banana | 56:20:24 | Consumer preferred, decrease wheat importation, increased nutritional composition | (Inyang & Nwabueze, 2020) |
| Fonio, CMC | 96:4 | Comparable to 100% wheat bread | (V. A. Jideani et al., 2007) |
| Fonio, Potato starch, Yeast, Soybean | 73:20:2:5 | Protein, nutrients, sensory | (V. Jideani et al., 2008) |
| Fonio, malted Bambara nut, Date palm | 60:10:30 | Gluten and sugar free, consumer acceptability | (Agu et al., 2020) |
| Fonio, Bambara nut, Plantain | 80:10:10 | Protein, fiber, nutrients | (Agu et al., 2014) |

**Table 2 (cont'd)**

| | | | |
|---|---|---|---|
| Fonio, Bambara nut, Carrot | | Protein, b-carotene, minerals | (Okafor, 2016) |
| Fonio, Soybean, Carrot, Milk flavor | 70:15:10:5 or 60:25:10:5 | Nutrients, functional properties, sensory characteristics | (Ukeyima et al., 2019) |
| Fonio, Bambara nut, Xanthum Gum | 75:25:3 | Gluten free, consumer acceptability, comparable to wheat bread in storage and flavor traits | (C. e. Chinma et al., 2015) |
| Fonio, Soybean, Sesame | 70:20:10 | Chemical and functional properties | (Ikujenlola, 2008) |
| Fonio, Soybean, Mango | | Protein, fat, energy, but low in micronutrients | (Combo et al., 2020) |
| Fonio, Soybean husk | 97.5 : 2.5 | Fiber, minerals, fats, proteins, consumer acceptability, texture | (Adekunle, 2018) |
| Fonio, Pigeon Pea | 70:30 | Protein, antinutrients | (Olagunju et al., 2018) |
| Fonio, Pigeon Pea | | Protein, ash, amino acids, vitamins, sensory analysis | (Babarinde, Adeyanju, et al., 2020) |
| Fonio, Moringa | 88:12 | Protein, fiber, fats, vitamins, minerals | (Raji et al., 2018) |
| Fonio, Orange Peel | 95:5 | Phytochemicals, sensory properties, consumer acceptability | (J. Ayo, Ayo, et al., 2018) |
| Fonio, Tigernut | | Fiber, fat, crispiness, texture | (Adekunle et al., 2018) |

**Table 2 (cont'd)**

| | | | |
|---|---|---|---|
| Fonio, Tigernut, Sorrel Seed | 50:45:5 | Protein, amino acids, fatty acids, minerals | (Adesida, 2020) |
| Fonio, Mushroom | 95:5 | Sensory, consumer acceptability | (J. Ayo, Ojo, et al., 2018) |
| Fonio, guava | 95:5 | Protein, ash, fat, fiber, consumer acceptability | (J. A. Ayo et al., 2020) |
| Fonio, Sandpaper leaf | 96:4 | Better hypertensive-diabetic properties | (Oboh et al., 2021) |
| Fonio, Mango kernel, Soy Cake | | Protein, Fiber, Flavonoid, phenol, less antinutritients | (Olorunfemi et al., 2022) |
| Fonio, Banana Peel | 75:25 | Comparable to 100% wheat bread | (J. Ayo et al., 2022) |
| Fonio, Baobab | 70:30 | Minerals, antinutrients, protein | (Obizoba & Anyika, 1994) |

CMC= carboxymethylcellulose

**Supplemental Table 3: List of starch modifications**

| Modification | Properties | Potential uses | Citation |
|---|---|---|---|
| Acetylation | Reduced physiochemical properties: Foaming, amylose content, true density, bulk density, water absorption capacity, ash content, and pH | | (Emeje et al., 2012) |
| Acid hydrolysis | Improved physiochemical and compaction properties | Compressible excipients | (Akin-Ajani et al., 2014) |

**Table 3 (cont'd)**

| | | | |
|---|---|---|---|
| Succinylation | Functional and morphological properties identified | Gums in food application | (Arueya & Oyewale, 2015)<br>(Olubusoye et al., 2021) |
| Oxidization | Improved stability | Dispersants, emulsifying agent, surface sizing, adhesive, disintegrants, excipients, and flocculants | (Isah et al., 2015) |
| Acid | Improved disintegrant properties<br>Comparable to corn starch disintegrants | Paracetamol tablet material | (Akin-Ajani et al., 2014) |
| Citric acid | Improved functional properties | Industrial uses | (Alimi & Workneh, 2018) |
| Carboxymethylation<br>Pregelatinised | Improved drug release properties | Pharmaceutical uses | (Omoteso et al., 2019) |
| Pregelatinised | Low onset of plastic deformation, increased crushing strength, disintegration, binder concentration, and dissolution time | Paracetamol tablet material | (J. K. Muazu et al., 2009) |

# 4. GROWING FONIO IN MICHIGAN: THE EFFECT OF SEEDING AND FERTILIZER RATES ON FONIO GRAIN YIELD, BIOMASS PRODUCTION, AND FORAGE QUALITY

## 4.1 Abstract

Crop diversity is essential in supporting many ecosystems' services including the resilience of agroecosystems. As climate change increases stressors, resiliency is essential for food and nutritional security. Greater utilization of minor crops can benefit U.S. cropping systems by building resiliency and filling specific niches. Fonio is a small grain traditionally grown in West Africa with great potential as a climate smart crop. Lack of global recognition has limited crop improvements and optimization of production practices. To test fonio in a new environment and explore its uses, fonio was grown in Western Michigan in 2021 and 2022. Two trials were conducted to test seeding rates and fertilizer rates. Total above ground biomass, grain yield, growth parameters, and forage potential were measured. The results highlight several challenges associated with fonio production including lack of flowering, weed management, and grain processing. Lower seeding rates and low fertilization increased biomass yields but had little to no effect on grain yields. Relative forage quality was high (130-150) when cut at booting, but yields were low (2249-5585 kg/ha) in comparison to other forages. Fonio may be cut several times for forage, but quality is reduced with subsequent cuttings. Research is needed to understand how variety and environments affect fertilizer response and forage quality, and to continue evaluating fonio within U.S. cropping systems.

## 4.2 Introduction

Diversity in agricultural systems is essential for supporting ecosystem services. Increasing functional diversity is known to improve long term community productivity and therefore soil health such as increased nitrogen, potassium, calcium, magnesium, and carbon (Dybzinski et al., 2008; Furey & Tilman, 2021). Addition of a single crop in rotation can increase soil carbon, nitrogen pools, and soil microbial biomass (McDaniel et al., 2014). Proper management of diversity can also prevent pest and disease outbreaks, reducing pesticide application. For example, an infestation of fall army worm was reduced 70-96% by increasing the number cover crops planted in a mixture (Meagher et al., 2022). On a landscape scale, diversity increases the density and species richness of pollinating insects potentially increasing yield over time (Aguilera et al., 2020; Raderschall et al., 2021). In integrated crop-livestock systems, greater forage diversity can improve yields and economic return (Sanderson et al., 2013) while providing a more diverse diet for livestock.

Crop diversity has additional benefits for resilience and stability as stress on agricultural systems increase due to climate change. Climate change is impacting temperature and precipitation throughout the U.S. by making weather events more extreme like long droughts, more intense storms, and hotter summer temperatures. As climatic variability increases, diversity in species or variety may improve yield stability across environments (Bybee-Finley &

Ryan, 2018; Reiss & Drinkwater, 2018). Increasing the number of crops grown regionally or on a farm scale will decrease the likelihood of complete crop loss through the insurance hypothesis (Lin, 2011). Resilience of agroecosystems to maintain functionality during or after a disturbance increases with improved ecosystem function. Functional diversity improves ecosystem function by increasing soil fertility and water conservation (Altieri, 2004). Climatic stressors will also likely increase biotic stress from pests and pathogens, increasing the importance of pest management and the use of crop diversity to prevent outbreaks.

Minor crops offer an opportunity to increase biodiversity and fill niches which may not yet be filled by major crops. Many of these minor crops are under-researched and are used in the U.S. as cover crops, niche grains, or forage crops. Crabgrass (*Digitaria sanguilis*) is often viewed as a weed in the United States but is also a drought tolerant forage crop that can increase the water use efficiency of U.S. pastures (Gelley et al., 2020). Cowpea and sun hemp used as cover crops in southern Texas and Florida may reduce the pressure of fall army worms (Meagher et al., 2022). Tef, a small grain from Ethiopia, is grown in the U.S. as a grain for human consumption or as a high quality forage crop. As a forage, tef is grown during the hottest and driest summer months with high quality suitable for horse feed (*Fitting Teff into the Horse Diet*, n.d.). As a grain, tef can be processed into a gluten free flour which will aid those with celiac's disease or gluten intolerance (*Teff Is a Healthy Wheat Alternative*, n.d.). Fonio is another small grain from West Africa that is drought tolerant and may benefit the resilience of U.S. agroecosystems.

In West Africa, farmers and crop stewards have been cultivating a small grain, fonio (*Digitaria spp.*), for thousands of years. This tiny grain is a warm season grass of high value to farmers in the region as a nutritious crop for low fertility sites with drought tolerant properties ((Fogny-Fanou et al., 2010a; Vall et al., 2011b). Often, it is produced at the end of many crop rotations without external inputs (Kanlindogbe et al., 2020). In U.S. systems, fonio would likely need very few external inputs and may be grown during drought or as a second crop. Fonio is also known to have a negative effect on the lifecycle of certain infectious fungus species (Kanlindogbe et al., 2020; Ndiaye & Termorshuizen, 2008), making it a possible cover or rotation crop to prevent pest outbreaks. With its preserved genetic diversity, there may be other unidentified traits. Just in Togo, 42 different varieties of fonio were characterized with a variety of agronomic attributes (Adoukonou-Sagbadja et al., 2008).

In U.S. systems, fonio may also be used as a niche grain for brewing or eating. It is growing in popularity in restaurants in the United States and there are several fonio brands currently being imported to the U.S. A Brooklyn brewery is currently selling beer made from fonio grains (Swierk, 2022) and a chef in New York is developing recipes for Western consumers (Hunt, 2020). As with quinoa and tef, fonio may find a place is U.S. food systems as a healthy alternative to major grains.

Fonio may have an economic advantage as a dual purpose crop. It is known that fonio hay is used to feed animals by grazing or cutting and storing (Cruz et al., 2016). Akinfemi (2012) found that fonio straws averaged 6.28% crude protein and increased to 7.69% crude protein when fermented for silage. In vitro digestibility also improved as fonio straw was fermented for silage. However, it is unknown how fonio forage, straw, and silage compares in nutrients or in yield to other common forages.

The lack of global recognition has limited formal improvement such as optimized and mechanized production or breeding improved varieties. Despite the many advantages, fonio has low and variable grain yield (210-1969 kg/ha) and the forage yield is unknown. Research through field trials is needed to better understand how fonio responds to production parameters like seeding rate and fertilizer. Recent studies in West Africa show that fertilizer can improve fonio grain and biomass yields with the optimal range of nitrogen being between 15-40 kg/ha (Amekli, 2013; Bakare & Ochigbo, 2003; S. Dachi et al., 2017; Gigou et al., 2009; Konaté et al., 2021). Planting strategy such as drilling and optimal planting time also increase yields (S. Dachi et al., 2017; M. Gueye et al., 2015). However, to the author’s knowledge, there are no published studies recording fonio growth in the U.S.

Before it can be incorporated into U.S. crop systems, management strategies must be explored. Specifically, it is unknown how fonio will grow in Western Michigan, if it will produce grain, or the forage potential. There are many gaps in our knowledge of fonio growth and potential niches. This research explored several aspects of fonio production in Michigan with a focus on seed and fertilizer rates, but also observing varietal differences in growth and forage quality. The purpose of this research is to characterize fonio production in a new environment while studying specific production parameters and potential forage uses. The research objectives were to:

1. Characterize fonio growth habit, forage yield, and forage quality in a new agroecosystem
2. Determine how fertilizer rate affects lodging, total biomass, grain yield, and plant growth
3. Determine how seeding rate affects lodging, total biomass, grain yield, plant growth characteristics, and forage yield and quality

To the author's knowledge, fonio has never been grown in the USA, thus this research will contribute to the literature on optimized crop and forage production and will characterize fonio growth in Michigan, USA. This research is important to better understand how fonio grows in Michigan, potential challenges, and basic management strategies.

## 4.3 Methods

Study Site Preparation

Field trials measuring a) seeding rate (SS Study) b) fertilizer rate (NPK study) were conducted over two field seasons (2021 and 2022). Only in the 2022 field season, additional trials measuring c) interaction effects between seeding rate and nitrogen and d) observations of six different varieties were conducted. Both years, trials were planted on an organically managed vegetable farm called Fat Blossom in Allegan, MI with a temperate climate averaging 990 mm of rain during the growing season. A single variety and single seed lot of fonio (except for variety trials), originating from eastern Guinea, was planted both seasons with seeding rates adjusted on a live seed basis over the two years (80% in 2021 and 75% in 2022). The 2021 field study was planted June 30 and the 2022 field season was planted June 1. The first year was planted late due to heavy rainfall and availability of seed. The second year was planted earlier to ensure full grain fill before the first frost.  Both trials had four replicates and were organized in a random complete block design, blocked by field slope. Seeds were broadcast and then lightly raked to incorporate the seed. To combat weed pressure, fields were cultivated three days before planting and the day of planting. Manual weeding of all distinguishable weeds (mostly broadleaves) was completed in the third and fifth week. In the 2022 field season, another major weed, stinkgrass (*Eragrostis cilianensis*), was distinguishable from fonio when flowering. After fonio booting stage, the majority of the stinkgrass seed heads were removed to help ensure fonio grain purity.

Experiment protocol

A) Seeding rates of 4, 8, 16, and 32 (only 2021) kg/ha were used to measure the effect or seeding rate on fonio growth parameters and yields. In West Africa, fonio is planted at a rate of 30-40 kg/ha with records of high seeding density of 70 kg/ha and lower rates for sowing in rows at 18 kg/ha (Cruz et al., 2016). In this study, we tested the lower range of seeding rates. The highest seeding rate was not included in the second season due to limited seed supply. The plots were 1.0 x 3.0 m with 30 cm in between plots. No fertilizer or other inputs were used.

B) Nitrogen rates of 0, 19.5, 27.8, or 52.2 kg N/ha in one, two, or three split applications were used to measure the effect on fonio growth parameters and yields. We incorporated with total amounts based on previous research using a range of 0-60 N kg/ha (Amekli, 2013; Bakare & Ochigbo, 2003; S. Dachi et al., 2017; Gigou et al., 2009). Fertilizer was applied at three rates during planting (0, low, high) and once or twice in a split application during the growing season (+1, +2) for a total of 7 treatments. Organic poultry manure litter was used and contained 2-3-4 NPK. The fertilized plots were 1.0 x 1.0 m and planted at a seeding rate of 24 kg/ha.

C) In 2022, a two factor study plot was planted with a low fertilizer rate (19.5 kg N/ha) incorporated at planting and a low seeding rate (4 kg/ha). From this, a two factor comparison was able to explore interactions between fertilizer rate and seeding rate.

D) In 2022, a variety observation was planted with five different varieties from Mali. Varieties 1, 2, and 4 were planted at rate of 49 kg/ha and varieties 3 and 5 were planted at a rate of 59 kg/ha. No inputs were used.

Data Collection

Prior to planting, soil at depth of 20 cm was collected in 10 random locations throughout each block and homogenized. The samples were dried and analyzed at A&L Labs for nutrient content. Soil texture analysis was completed by the micropipette method (adapted from Benbi et al., 1996) in the lab.

In both years, forage quality and yield samples were taken at late booting stage (cut 1) of development 50 days (2021) or 56 days (2022) after planting in the seeding rate trial plots and in the variety observation plots (only 2022). In both years, another forage quality and yield sample were taken at grain maturity 80 days (2021) or 120 days (2022) after planting (cut 2). Only in 2022, the first forage sample quadrant was recut for forage quality and yield analysis (cut 3). To collect all samples, a 0.5$m^2$ quadrat was randomly thrown into a plot. All non-fonio plants were removed and the number counted and recorded. The percentage of fonio plants at the flowering stage was also recorded. All fonio plants were cut a few inches above soil line (approximately 4 cm.), fresh weight was measured, and samples were dried for 72h until consistent mass before analysis with Near Infrared Spectroscopy (NIR) which measured micronutrients, crude protein, and fiber contents. Pre-established equations for mixed grasses were used.

To determine plant characteristics and possible changes in plant partitioning, individual plants sample were collected. At harvest, five (seeding rate plots) or three (nitrogen rate plots) flowering fonio plants were randomly selected and measured for height, fresh weight, number of tillers, panicles, and racemes. Each plant was cut at soil line, dried for five days, and weighed. Total plant density was back calculated by dividing the total plot biomass by the average individual plant. Each plot was given a lodging score (1-10) based on the extent and severity of lodging (Bitarafan et al., 2019). For example, a lodging score of 5 would mean either the entire plot was slightly fallen over, or one small portion of the plot was completely lodged. The entire plot was harvested by cutting each plant at the soil line and transported to the drying location. To dry, biomass was spread out on a tarp and turned weekly. After the biomass dried (about four weeks), the fonio was threshed by stomping on the biomass and shaken by hand. The grain was collected on a tarp. The dry straw was discarded, and the grain was sieved for final yield measurements. Grain was left with hull and without complete purity from weed seed.

Statistical Analysis

The statistical software, R (Version 1.4.1717), was used to visualize and analyze the data. Residuals were assessed for normality via data visualization. Homogeneity of variance was examined by Levene's test with the squared and absolute values of residuals ($P \leq .05$). No transformations were needed. To measure the effect of treatment and year on the response variables, liner mixed models were used with treatment and year as fixed effects and block as random effects. The response variables from the experiments include whole plot measures: above ground biomass, forage quality (SS only), lodging score, grain yield (SS only), and individual plant parameters: plant height, plant dry mass, number of tillers, panicles, and racemes. Fixed factors were treatment (either seeding rate or nitrogen rate), year, cut (forage only), and the interactions. Models with and without interaction effects were compared using AIC values and model with the lowest AIC value were used for final analysis. Analysis of variance was used to test for significance and Tukey test was used post hoc to compare treatments.

## 4.4 Results

Study Sites

Weather conditions differed between years with the recorded average temperature and precipitation summarized in Table 4.1. Yearly data was collected from the enviroweather platform from MSU and yearly averages from weatherspark.com. The first field season was slightly warmer and drier than the second year, but the major difference between years was monthly precipitation. In 2021, there was high precipitation right before planting then lower than average for the rest of the growing season. Most notably, there was low rainfall after planting and a 4 week drought from the end of August to the end of September during crucial grain-fill period (Figure 4.1). In 2022, precipitation was close to monthly average, with a temporal drought in the beginning of the growing season for two weeks.

**Table 4.1: Total monthly precipitation and mean low-high temperature for Allegan, Michigan during 2021 and 2022 field seasons and normal yearly averages.**

| Year | Temperature (low-high ºC) | | | Total Monthly Precipitation (mm) | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | June | July | August | May | June | July | August | September | October |
| 2021[1] | | 17-27 | 17-29 | 33.8 | 220 | 50.3 | 57.7 | 34.5 | 129.5 |
| 2022[1] | 13-27 | 16-28 | 16-27 | 115 | 65.3 | 108 | 89.9 | 34.6 | 62.0 |
| Avg[2] | 15-26 | 17-28 | 16-26 | 78.6 | 76.2 | 70.9 | 77.6 | 81.1 | 75.4 |

[1]Yearly data from https://enviroweather.msu.edu/weathermodels/weathersummary

[2]Averages from https://weatherspark.com/y/146616/Average-Weather-at-Gerald-R.-Ford-International-Airport-Michigan-United-States-Year-Round#Figures-Temperature

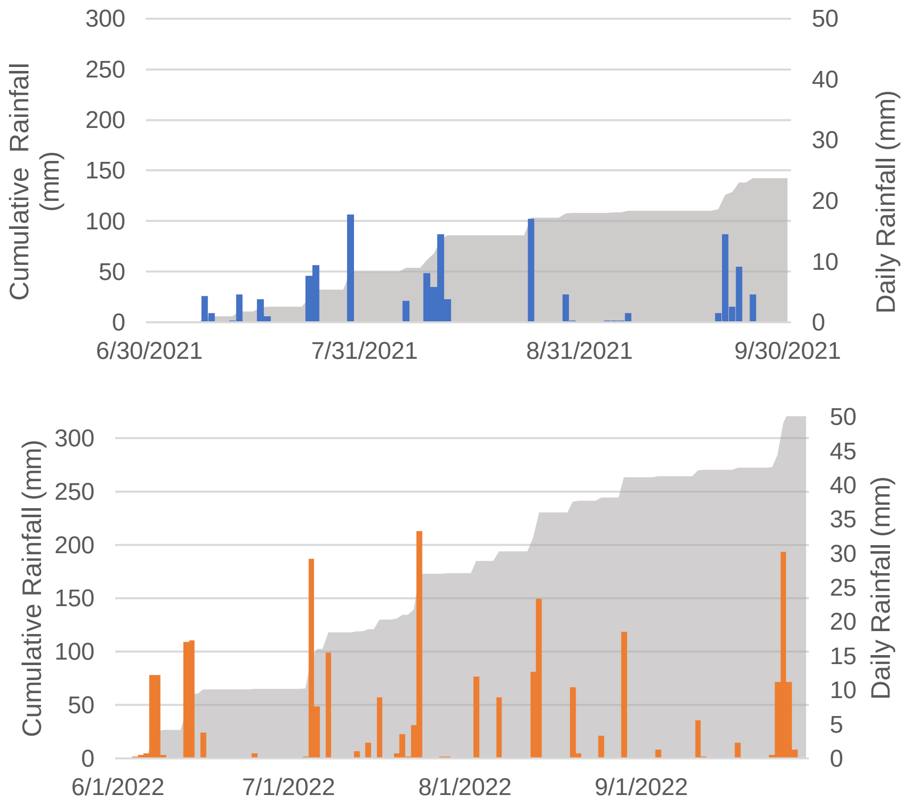


**Figure 4.1: Daily and cumulative rainfall from planting to harvest at Fat Blossom Farm, Allegan, MI in 2021 and 2022.** Cumulative rainfall from planting to harvest in gray on the left axis and daily rainfall in orange (2022) or blue (2021) on the right axis.

The soil texture was a major difference between study sites. The field in 2021 had higher sand content compared to the 2022 field (Table 4.2). Between the sites for SS study, 2021 had higher sand and organic matter content. Between the site for the NPK study, sand content was much higher in the 2021 site and organic matter was lower. Between the study sites in 2021, the NPK site had higher levels of sand (84.0% vs. 74.2%) and lower amounts of organic matter (OM) (1.25% vs 2.05%) compared to the SS site.

**Table 4.2: Soil nutrients analysis for each study and block at Fat Blossom Farm, Allegan, MI in 2021 and 2022**

| Year | Study | Block | Clay % | Sand % | Silt % | pH | % OM | P ppm | K ppm | Mg ppm | Ca ppm | CEC | K Sat % | Mg Sat % | Ca Sat % |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 2021 | SS | 1 | 4.4 | 73.2 | 22.4 | 5.3 | 2.1 | 109 | 54 | 90 | 655 | 6.6 | 2.1 | 11.4 | 49.9 |
| | | 2 | 5.2 | 73.6 | 21.1 | 5.3 | 2.0 | 101 | 36 | 89 | 511 | 5.8 | 1.6 | 12.8 | 44.1 |
| | | 3 | 4.9 | 74.8 | 20.4 | 5.4 | 2.1 | 102 | 41 | 97 | 538 | 4.8 | 2.2 | 16.8 | 56 |
| | | 4 | 4.8 | 75.1 | 20.1 | 5.2 | 2.0 | 99 | 44 | 96 | 543 | 6.0 | 1.9 | 13.3 | 45 |
| | NPK | 1 | 4.0 | 83.9 | 12.1 | 5.6 | 1.1 | 141 | 57 | 82 | 556 | 4.8 | 3 | 14.2 | 57.8 |
| | | 2 | 3.2 | 84.2 | 12.5 | 5.7 | 1.2 | 157 | 48 | 88 | 464 | 4.4 | 2.8 | 16.8 | 53 |
| | | 3 | 3.6 | 83.8 | 12.6 | 5.6 | 1.3 | 143 | 48 | 89 | 660 | 5.4 | 2.3 | 13.8 | 61.5 |
| | | 4 | 3.6 | 84.2 | 12.2 | 5.8 | 1.4 | 166 | 39 | 80 | 667 | 5.3 | 1.9 | 12.6 | 62.9 |
| | | | * | * | * | * | * | * | | * | | | | | * |
| 2022 | SS | 1 | 4.2 | 68.7 | 27.2 | 5.7 | 1.7 | 81 | 53 | 97 | 582 | 5.1 | 2.7 | 16 | 57.6 |
| | | 2 | 4.4 | 70.7 | 25.0 | 5.7 | 1.5 | 76 | 53 | 90 | 536 | 4.8 | 2.9 | 15.7 | 56.2 |
| | | 3 | 5.3 | 65.8 | 28.9 | 5.7 | 1.5 | 81 | 66 | 105 | 760 | 6.0 | 2.8 | 14.5 | 62.9 |
| | | 4 | 5.7 | 70.7 | 23.7 | 5.6 | 1.4 | 85 | 57 | 89 | 492 | 4.5 | 3.2 | 16.3 | 54.1 |
| | NPK | 1 | 5.40 | 70.0 | 24.6 | 5.5 | 1.6 | 81 | 82 | 96 | 885 | 7.8 | 2.7 | 10.2 | 56.5 |
| | | 2 | 5.47 | 69.7 | 24.9 | 5.6 | 1.4 | 76 | 65 | 94 | 524 | 4.8 | 3.5 | 16.4 | 54.9 |
| | | 3 | 5.51 | 71.4 | 23.1 | 5.6 | 1.5 | 79 | 70 | 86 | 508 | 4.6 | 3.9 | 15.5 | 54.8 |
| | | 4 | 6.04 | 69.9 | 24.1 | 5.5 | 1.5 | 88 | 61 | 88 | 731 | 6.9 | 2.3 | 10.6 | 52.6 |
| | | | | | | * | | | * | | | | | | |

* Significant differences between study sites are indicated by an asterisk at the bottom of the column within the year.

Observation and Development

A single variety of fonio was planted for the seeding rate and fertilizer trials. Little was known about this variety except that it was gifted by a farmer near KanKan, Guinea. From the two field seasons, it can be determined that this variety flowers between 52-60 days and matures 17-41 days after flowering (Table 4.3). This variation is possibly due to differences in water availability throughout the field. Both flowering and maturation occur heterogeneously throughout the plots and fields with flowering still occasionally occurring at harvest when most of the grain is mature. After grain matures, this variety also has a tendency to shatter. Lodging was mostly observed after animals use the fields for bedding or after storms.

There was also a challenge with the variety observations and the 2021 NPK trials not flowering. The 2021 field trials for the SS and the NPK study were in the same field but the SS flowered and the NPK study did not. The difference between the sites of the two studies in the same field was soil texture and slope of the field. The general observations of the single variety are summarized in table 4.4 across all of the years and trials.

**Table 4.3: Days from planting to: emergence, boot, flower, grain maturity, and harvest for the seeding rates, fertilizer rates, and variety trials at Fat Blossom Farm, Allegan, MI in 2021 and 2022**

| Planting date | Study | Emergence | Boot | Flower | Grain Maturity | Harvest |
|---|---|---|---|---|---|---|
| June 30 2021 | SS | 8 | 52 | 60 | 77-81 | 77-81 |
| | NPK | 8 | na | na | na | 122 |
| June 1 2022 | SS | 6 | 57 | 57 | 100-121 | 100-121 |
| | NPK | 6 | 50 | 52-60 | 92 | 92 |
| | Var | 7 | na | na | na | na |

**Table 4.4: Varietal characteristics of the single variety from Kankan, Guinea grown at Fat Blossom Farm, Allegan, MI in 2021 and 2022. The range indicating the average values between the two studies.**

| Trait | |
|---|---|
| Days to Flower | **50-60** |
| Days to Grain Maturity | **77-120** |
| Avg. Lodging Score* | **5-6** |
| Avg. Plant Height (cm) | **66-74** |
| # tillers | **3-4** |
| # panicles | **6-10** |
| # racemes | **30-50** |
| Growth Habit | **Erect** |
| Grain Color | **Brown/Tan** |

* Lodging score based on a 1-10 scale between complete lodging (10) and no lodging (1).

<u>Seeding Rate Study (SS)</u>

For above ground biomass, there was an interactive effect between year and treatment, and year was a significant additive effect (f=9.31, p= 0.006). Between years, the total aboveground biomass (DM) was greater in the second year (Table 4.5, Figure 4.2). In the first year, seeding rate treatments did not affect total biomass (f=0.66, p=0.592). In the second year, the highest seeding rate had a higher biomass compared to the lowest seeding rate (p=0.016). These results may be explained by total plant density in each plot which followed a similar trend to biomass results. For grain yield, there was no interaction between year and treatment, and both seeding rate (f=5.48, p=0.007) and year (f=8.46, p=0.009) had additive effects. The second year had overall higher grain yields compared to the first year. In both years, higher seeding rates had lower grain yield. Rates of 4 and 8 kg/ha had higher grain yields compared to 16 and 32 kg/ha in 2021 and the rate of 8kg/ha had higher grain yield compared to 16 kg/ha in 2022.

Lodging was not affected by year (0.712, p= 0.410), treatment (f= 0.422, p= 0.739), or an interaction effect in either year. Increased lodging was attributed to deer using the field to bed according to observations made by the farmer and the lodging patterns (Figure 4.3) in the first year and storm damage in the second year. Average plant height at grain maturity was not different between years. In both years, the 16kg/ha seeding rate had shorter plants compared to the lower seeding rates. In 2021, the highest seeding rate, 32 kg/ha, also had taller plants compared to the 16kg/ha seeding rate.

Individual plant morphological traits were different between years (Table 4.5). The number of tillers per plant were not affected by seeding rate but were significantly affected by year (f=24.9, p<0.001) with number of tillers being higher in the first year compared to the second year. Similarly, the number of panicles (f=16.6, p<0.001), racemes (f=30.4, p<0.001), and individual plant dry mass (f= 18.4, p<0.001) were unaffected by treatment and higher in the first year compared to the second year.

**Table 4.5: Plot and individual plant results for seeding rate study at Fat Blossom Farm, Allegan, MI in 2021 and 2022**

| Year | Seeding Rate (kg/ha) | Plot Data | | | Individual Plant Data | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | DM (g/m$^2$) | Lodging Score** | Grain (g/m$^2$) | Height (cm) | DM (g) | tillers | panicles | racemes |
| 2021 | 4 | 531 ± 33 $^a$ | 5.0 | 14.4 ± 2.1 $^a$ | 76.75 $^a$ | 2.82 | 5.3 | 10.4 | 58.5 |
| | 8 | 573 ± 17 $^a$ | 6.0 | 12.1 ± 3.5 $^a$ | 78.91 $^a$ | 3.85 | 5.6 | 14.7 | 80.3 |
| | 16 | 532 ± 42 $^a$ | 5.5 | 5.03 ± 0.46 $^b$ | 68.80 $^b$ | 2.67 | 5.3 | 11.9 | 60.5 |
| | 32 | 596 ± 38 $^a$ | 5.5 | 5.81 ± 1.3 $^b$ | 77.10 $^a$ | 3.05 | 5.1 | 12.9 | 65.6 |
| 2022 | 4 | 576.5 ± 46 $^a$ | 4.25 | 19.98 ± 2.9 $^{ab}$ | 76.05 $^a$ | 1.85 | 3.0 | 7.5 | 33.9 |
| | 8 | 694.5 ± 62 $^{ab}$ | 4.25 | 23.59 ± 4.6 $^a$ | 74.30 $^a$ | 1.60 | 3.2 | 6.6 | 29.1 |
| | 16 | 893 ± 107 $^b$ | 6.25 | 9.79 ± 1.3 $^b$ | 64.00 $^b$ | 1.29 | 3.3 | 6.9 | 25.5 |
| | | * | | * | | * | * | * | * |

*Letters indicating statistically significant differences between treatments within a single year (p<0.05), no letters indicate no statistically significant differences between treatments. Asterisks indicate differences between years.
**Lodging score based on a 1-10 scale between complete lodging (10) and no lodging (1).

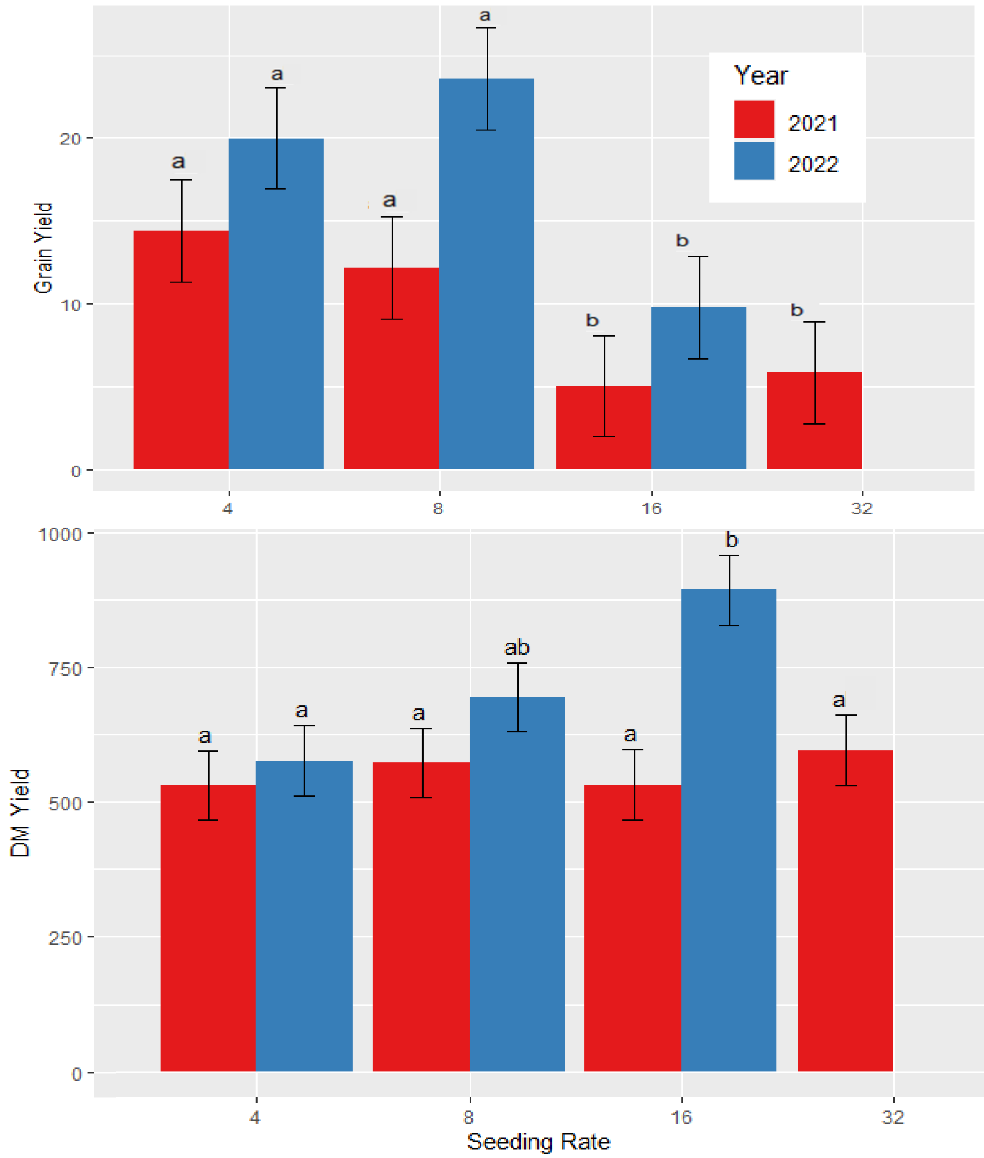


**Figure 4.2: Total aboveground biomass yield (DM) and grain yield for seeding rates at Fat Blossom Farm, Allegan, MI in 2021 and 2022.**

**Figure 4.3: Images of lodging at Fat Blossom Farm, Allegan, MI in 2021 field season**, comparing block 1 (lodging score of 3, left) and block 3 (lodging score of 6, right). The area where a deer used the field for bedding is boxed in green.

Fertilizer Study (NPK)

Total above ground biomass was affected by treatment (f=3.24, p=0.0099) and year (f=4.8545, p=0.0327) without interaction between the two terms. Between the two years, at every treatment level, the 2022 field season had higher biomass yields. In both years, every treatment except for the low treatment, was different from the control, meaning that additions of fertilizer greater than 19.5 kg N/ha produced greater biomass (Figure 4.4). In 2021, compared to the control, the highest fertilizer treatment (high+2) increased biomass by 63% and the lowest fertilizer amount increased biomass by 23% (Figure 4.5). These results were not caused by increased plant densities since density was the same in each plot (f=0.785 , p=0.586). Grain yield was not collected in 2021 due to lack of flowering in the plots. In 2022, fertilizer treatment had no effect on final grain yield (f=0.3866, p=0.878). No other factors (dry weight, plant height, etc.) were correlated to final grain yield.

Lodging was not affected by treatment or year. Plant height was affected by year (f=113, p<0.0001) and not affected by treatment (f=0.93, p=0.48) or an interaction between terms. Plant height was greater at every treatment level in the 2022 field season.

Individual plant morphological traits were not different between years (Table 4.6). The number of tillers per plant were not affected by fertilizer rate (f=0.703, p=0.65) or year (f=3.39, p=0.072). Similarly, the number of panicles (f=0.733, p=0.29), racemes (f=0.783, p=0.593), and individual plant dry mass (f=0.593, p=0.733) were unaffected by treatment and year.

**Table 4.6: Plot and plant results from the fertilizer trials at Fat Blossom Farm, Allegan, MI in 2021 and 2022**

| Year | Fertilizer Rate | Plot Data | | Individual Plant Data | | | | |
|---|---|---|---|---|---|---|---|---|
| | | DM ($g/m^2$) ± SE | Grain ($g/m^2$) ± SE | Height (cm) | DM (g) | tillers | panicles | racemes |
| 2021 | 0 | 572.7 ± 43.9[a] | | 44.8 | 1.43 | 4.6 | 9.5 | 38 |
| | Low | 704.2 ± 30.5[ab] | | 43.1 | 1.08 | 2.9 | 4.8 | 22 |
| | Low+1 | 872.0 ± 38.2[b] | | 51.0 | 1.31 | 3.6 | 5.3 | 26 |
| | Low+2 | 865.2 ± 61.9[b] | | 49.0 | 1.09 | 4.1 | 7.5 | 34 |
| | High | 848.2 ± 27.7[b] | | 43.7 | 0.81 | 4.3 | 5.7 | 30 |
| | High+1 | 935.5 ± 52.4[b] | | 49.9 | 0.93 | 3.0 | 5.3 | 21 |
| | High+2 | 937.8 ± 61.1[b] | | 56.0 | 2.18 | 5.1 | 11.8 | 60 |
| 2022 | 0 | 732.5 ± 49.5[a] | 23.27 ± 5.5[a] | 73.1 | 1.26 | 2.9 | 5.1 | 25.4 |
| | Low | 920.0 ± 40.8[ab] | 21.08 ± 3.5[a] | 81.8 | 1.59 | 3.5 | 4.4 | 24.0 |
| | Low+1 | 903.8 ± 59.7[b] | 23.58 ± 5.9[a] | 79.8 | 1.43 | 2.9 | 5.0 | 26.7 |
| | Low+2 | 943.8 ± 46.2[b] | 22.31 ± 3.8[a] | 82.0 | 1.98 | 3.8 | 4.9 | 26.6 |
| | High | 1028 ± 21.7[b] | 17.24 ± 1.6[a] | 88.4 | 1.85 | 3.0 | 4.3 | 24.1 |
| | High+1 | 973.8 ± 100[b] | 21.66 ± 3.9[a] | 86.3 | 2.21 | 3.3 | 5.3 | 29.3 |
| | High+2 | 921.3 ± 30.7[b] | 23.28 ± 1.8[a] | 88.3 | 1.92 | 2.8 | 4.8 | 26.7 |
| | | * | | * | | | | |

* Average dry mass (DM) and distribution and individual plant parameters at each fertilizer rate. Letters indicate differences in treatments within a field season.

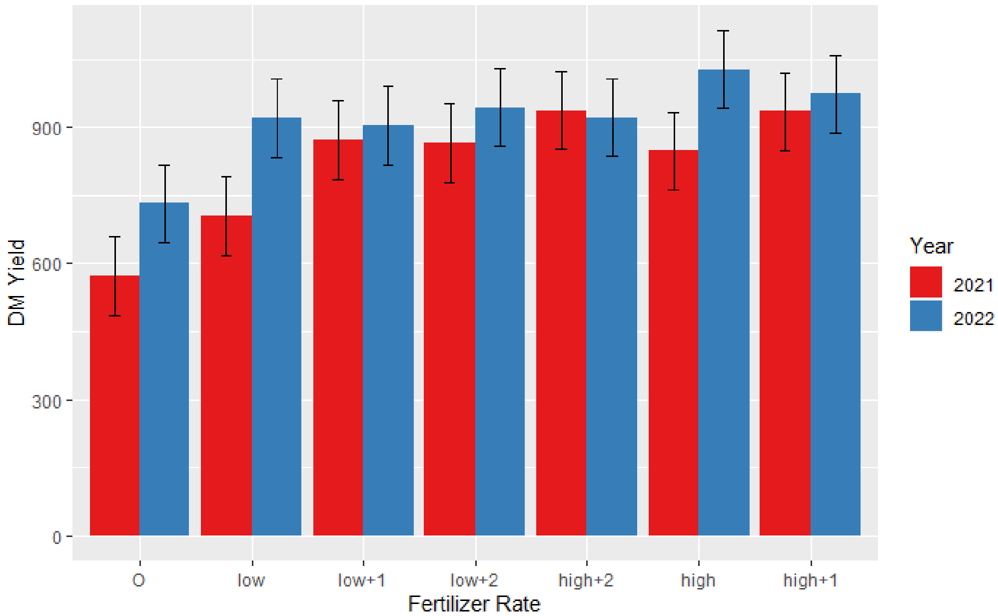


**Figure 4.4: Total aboveground biomass yield for each fertilizer treatment at Fat Blossom Farm, Allegan, MI in 2021 and 2022**

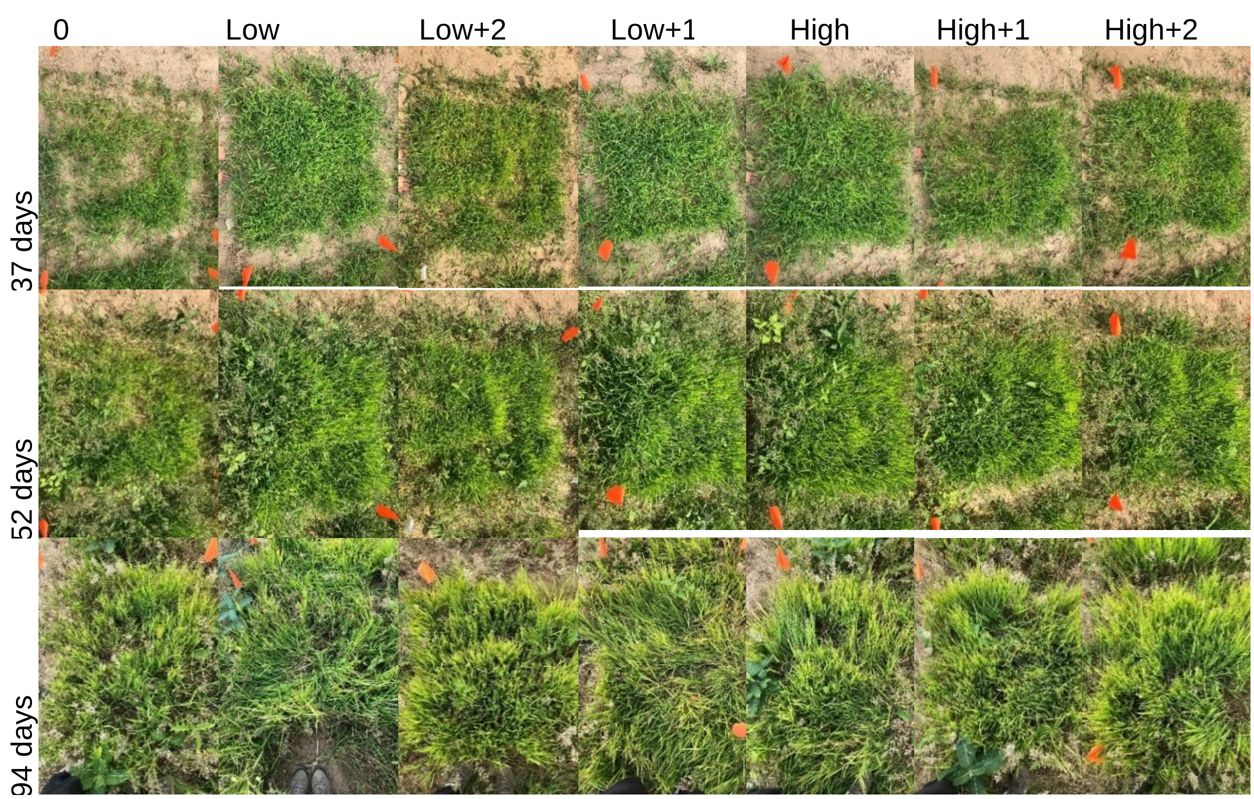


**Figure 4.5: A single replicate in 2021 season over three time points: at +1 and +2 fertilization and at harvest at Fat Blossom Farm, Allegan, Mi**

Interaction between seeding rate and fertilizer rate

In the exploratory study c) investigating the interaction between seeding rate and fertilizer, we had one year of data from 2022. For total above ground biomass yield, there was no interactive effect between seeding rate and nitrogen rate. Seeding rate, regardless of fertilizer rate, increased total aboveground biomass (Table 4.7). Fertilizer only increased biomass at higher seeding rates. Grain yield, lodging, and individual plant traits were all unaffected by fertilizer or seeding rate.

**Table 4.7: Plot and plant results from the fertilizer x seeding rate trials at Fat Blossom Farm, Allegan, MI in 2022**

| Fertilizer rate | Seeding Rate | Dry Mass ($g/m^2$) | Grain ($g/m^2$) | Lodge Score** | Height | #tillers | #panicles | # racemes | Ind. Dry mass |
|---|---|---|---|---|---|---|---|---|---|
| 0 | 4 | 576.50±46.0 [a] | 19.98±2.9 | 4.25 | 76.05 | 2.95 | 7.50 | 33.90 | 1.85 |
| 0 | 24 | 732.50±42.9 [b] | 23.27±4.8 | 6.25 | 73.08 | 2.92 | 5.08 | 25.42 | 1.26 |
| Low | 4 | 696.25±31.8 [ab] | 19.92±5.2 | 6.50 | 81.50 | 4.50 | 6.75 | 39.33 | 2.11 |
| Low | 24 | 920.00±35.4 [c] | 21.08±3.0 | 6.75 | 81.75 | 3.50 | 4.42 | 24.00 | 1.59 |

*Letters indicate differences in treatments within a field season. No letters demonstrate no difference between treatments.

**Lodging score based on a 1-10 scale between complete lodging (10) and no lodging (1).

Forage Yield and Quality

In both years, seeding rate had no effect on forage yields (f=1.827, p=0.155), crude protein (f=1.94, p=0.155), fiber content, or forage quality (f=2.32, p=0.110), and thus, seeding rate effect was excluded from the analysis. Forage yield (DM) was affected by cut (f=122, p<0.001), year (f=8.78, p=0.0047), and the interaction (f=18.36, p<0.001). Forage yield was greater during the 2021 field season compared to the 2022 field season (Table 4.8). Within each year, biomass increased with each cut. The recut of the first sample (cut 2) had lower biomass compared to an uncut sample (cut 3). The yield for the first cut on average across seeding rates was 123 $g/m^2$ and 45.8 $g/m^2$ in the first and second year (Figure 4.6). For crude protein, cut (f=138, p<0.001) and year (f=151, p<0.001) both had an affect with no interaction between terms. At each cut, crude protein was higher in 2021. For both years, the first cut had the highest crude protein. Within the second year, there was no difference in the crude protein content of the second cut and the recut of the first cut. For fiber content (both NDF and ADF), cut (f=453, p<0.001), year (f=130, p<0.001), and the interaction (f=360, p<0.001) had an effect. Fiber content was greater in the second year and increased with each cut. Similarly, relative forage quality was affected by cut (f=100, p<0.001), year (f=36.6, p<0.001), and the interaction (f=72.1, p<0.001). Between years, the second year had higher forage quality at the first cut (151 vs. 134), but the first year had higher forage quality at the second cut. In both years, the forage quality decreased with subsequent cuttings. In the second year, the recut had higher forage quality compared to the uncut sample.

**Table 4.8: Forage Potential Results from the seeding rate study at Fat Blossom Farm, Allegan, MI in 2021 and 2022**

| Year | Cut #** | DM (g/m$^2$) | CP | ADF | NDF | RFQ |
|---|---|---|---|---|---|---|
| 2021 | 1 | 123 ± 7.8 [a] | 15.3 ± 0.22 [a] | 31.91 ± 0.14 [a] | 60.0± 0.13 [a] | 134 ± 0.42 [a] |
| | 2 | 558 ± 19 [b] | 9.65 ± 0.39 [b] | 35.6 ± 0.27 [b] | 62.7 ± 0.41 [b] | 121 ± 2.0 [b] |
| 2022 | 1 | 45.8 ± 2.1 [a] | 11.0 ± 0.17 [a] | 29.7 ± 0.31 [a] | 53.7 ± 0.49 [a] | 151 ± 2.1[a] |
| | 2 | 288 ± 26 [c] | 4.40 ± 0.27 [b] | 41.6 ± 0.24 [c] | 70.7 ± 0.27 [c] | 107 ± 1.8 [c] |
| | 3 | 225 ± 24 [b] | 5.05 ± 0.35 [b] | 40.5 ± 0.17 [b] | 68.8 ± 0.36 [b] | 118 ± 2.5 [b] |
| | | * | * | * | * | * |

*Dry Mass (g/m$^2$) and NIRS forage quality results including: % Crude Protein (CP), % Acid Detergent Fiber (ADF), % Neutral Detergent Fiber (NDF), and Relative Forage Quality (RFQ). ± the standard error (SE). Letters indicate differences within years between cuts, asterisks indicate differences between years.

**Cut 1 was taken at the booting stage for optimal forage quality, Cut 2 was a separate cutting taken at grain harvest for optimal forage yield, Cut 3 was a re-cutting of Cut 1 taken at grain harvest

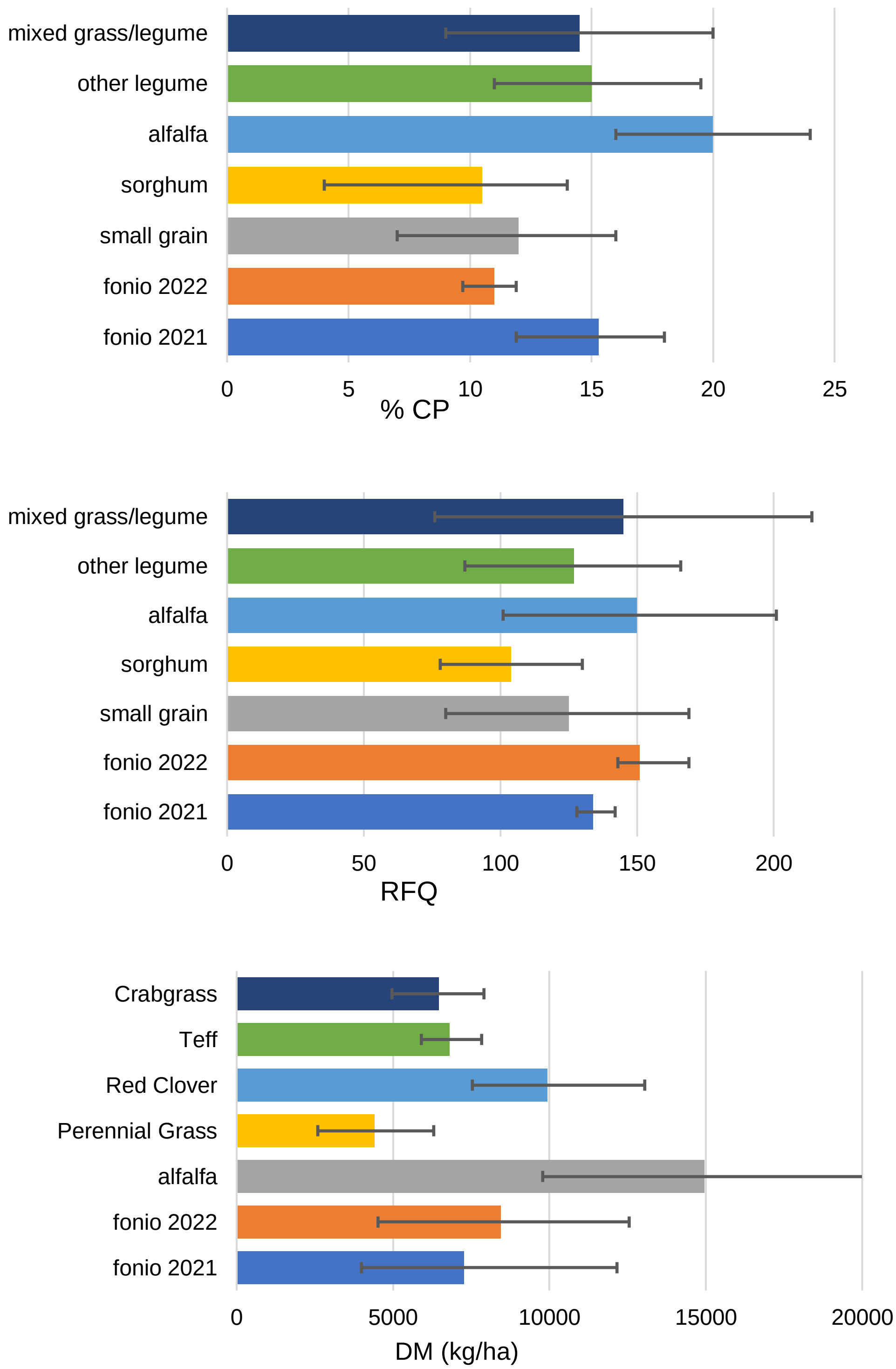


**Figure 4.6**: **Comparing crude protein (CP)[1], relative forage quality (RFQ)[1], and dry matter (DM, kg/ha)[2] across forage types.** The average (end of bar) and typical expected range (black bars).

[1] RFQ and CP data from various forage species submitted to the UGA Feed and Environmental Water Laboratory from July 2003 to February 2011. Data is adapted from *Understanding and Improving Forage Quality | UGA Cooperative Extension*. Data from our field trials added with calculated average values of fonio RFQ and CP and minimum and maximum indicated by the bars in 2021 field season and 2022 field season.

[2] DM data is adapted from the MSU forage connect variety trial results in Michigan during the years of 2019-2021. Data from our field trials added with calculated average values of fonio DM and minimum and maximum indicated by the bars in 2021 field season and 2022 field season.

Variety Trials

Five fonio varieties from Mali were planted for observation and tested for forage quality without replication in the second field season (Table 4.9). No flowering was observed in any of the plots for unknown reasons. Variety #4 suffered from an unknown leaf curling disease that plant diagnostics could not identify. Lodging was also observed in all varieties but not scored. The varieties had similar forage quality and biomass yield with variety 5 appearing to have higher biomass yield and quality in the first cut and higher quality but lower biomass yield in the second cut (not a re-cut). Generally, there were differences observed in forage quality and yield between varieties.

**Table 4.9: Forage Potential Results of different varieties from observational trial with single replicate in 2022**

| Cut | Variety | DM ($g/m^2$) | CP | ADF | NDF | RFQ |
|---|---|---|---|---|---|---|
| 1 | 1 | 58.29 | 11.02 | 29.04 | 51.00 | 142.3 |
| | 2 | 63.37 | 8.74 | 30.49 | 53.53 | 143.9 |
| | 3 | 54.87 | 9.06 | 29.62 | 53.16 | 147.5 |
| | 4 | 76.25 | 9.70 | 29.27 | 52.79 | 147.5 |
| | 5 | 79.56 | 9.85 | 29.25 | 53.09 | 148.2 |
| 2 | 1 | 497.5 | 2.22 | 39.50 | 70.63 | 99.6 |
| | 2 | 396.1 | 1.52 | 39.56 | 71.99 | 93.5 |
| | 3 | 355.5 | 1.77 | 40.54 | 72.59 | 92.4 |
| | 4 | 437.4 | 3.70 | 40.38 | 69.67 | 109.4 |
| | 5 | 286.4 | 4.53 | 41.78 | 70.35 | 112.3 |

*Dry Mass ($g/m^2$) and NIRS forage quality results including: % Crude Protein (CP), % Acid Detergent Fiber (ADF), % Neutral Detergent Fiber (NDF), and Relative Forage Quality (RFQ). Varieties 1, 2, and 4 were planted at rate of 49 kg/ha and varieties 3 and 5 were planted at a rate of 59 kg/ha. Cut 1 was taken at booting stage. Cut 2 was a separate cutting taken before frost.

## 4.5 Discussion

Seeding Rate Study

We examined the effect of seeding rate on plant growth and yields to determine optimal management practices in Michigan. According to Cruz et al (2016), fonio is traditionally planted at a rate of 30-40 kg/ha with records of high seeding density of 70 kg/ha and lower rates for sowing in rows at 18 kg/ha. In this study, we tested the lower range of seeding rates. The seeding rate increased above ground biomass only in the second year which may be explained by low precipitation in the first field season limiting plant growth. Other small grains also demonstrate increased above ground biomass as seeding rate increased (Baker, 1982; El-Lattief, 2014) most likely due to overall greater plant density per plot. Contrary to fonio studies comparing biomass and grain yields (Amekli, 2013) and other small grains (Baker, 1982; Dorval et al., 2015; El-Lattief, 2014; Schillinger, 2005), fonio grain yield was reduced by seeding rate and negatively correlated to biomass. Only tef grain and biomass yields have been observed to increase at lower sowing rates (Arefaine et al., 2020). The grain results are also not explained by plant morphological traits measured. In the second field season, increased reproductive panicles and racemes at lower plant densities were observed but were not statistically significant or observed in the first year. On average, the number of reproductive tillers, panicles, and racemes were greater in the first field season, but did not correspond to greater grain yields.

We hypothesized that both grain and biomass yields would increase as seeding rate increased but we found that only biomass was improved with greater seeding rates. These results were not explained by morphological characteristics but may be due to overall low grain yields and a different climate from the variety's origin. The seed variety grown originated from Kankan, Guinea which averages 590 mm of precipitation during the growing season. The average precipitation in Allegan, MI is 306 mm, almost half and was exasperated by temporal droughts throughout the growing season especially in 2021. This possibly led to overall low yields especially compared to average yields of fonio in Guinea (Figure 1.1). These results also may be affected by the different planting dates between the two years. A later planting date allowed for longer amount of time for total growth and biomass accumulation in the first season.

As hypothesized, average individual plant height was also impacted by seeding rate, but lodging was not. The seeding rate of 16 kg/ha produced shorter plants compared to the other seeding rates but did not correlate to less lodging. This is contrary to many findings where lodging and plant height are positively correlated (Arefaine et al., 2020; Dorval et al., 2015). The greater factors affecting lodging in the fonio plots were storm winds and animals. To further understand fonio response to lodging and height, more controlled studies may need to be done.

Nitrogen Rate Study

We examined the effect of fertilizer rate on plant growth and yields to determine optimal management practices in Michigan. In both field seasons, a positive trend was observed between fertilization and biomass. Fertilized plots with nitrogen greater than 19.5 kg N/ha had statistically significant different above ground biomass compared with those with less (0 and low treatments). These results are similar to studies from West Africa. Gigou et al. (2009) found that fonio responded to inorganic NPK fertilizers at low levels of fertilization (30 kg/ha) which increased grain yields by 22%. Amekli (2013) also determined that increased grain yields directly correlated with an increase of biomass. Grain yields from our study were not affected by fertilization or correlated with biomass yields. The lack of statistical differences between treatments in grain yield may be explained by the precipitation challenges explained above and demonstrates challenges with growing crops in new agroecosystems.

The results demonstrate an important risk when fertilizing fonio. The regions where fonio is grown, especially for food security and sustenance, are prone to drought. Fertilizer may have little to no affect during drought and there may not be a corresponding increase in grain yield. Using fertilizer does not guarantee higher yields since it is dependent on rainfall and many other factors. Maji & Imolehim (2013) also determined fertilization without fungicide application increased the severity of brown spot disease and decreased grain yields. Fertilizer may not guarantee increased grain yield for sustenance farmers because of nutrient availability also depending on soil moisture and precipitation.

Challenges Across Studies

Flowering is a challenge when growing a crop in a new environment because there are many biological and environmental factors that control grain development. In 2021, the fertilized field trial did not flower, but the seeding rate study, in the same field with the same climate and precipitation, did successfully flower and produce grain. The major differences between the two trials were soil organic matter and texture, two factors heavily influencing water holding capacity. The slope of the field may have drained water into the seeding rate plots. Low rainfall during the beginning of the season made water a limiting factor during crucial growth stages. We hypothesize that the nitrogen plots did not flower in 2021 due to lack of water, also possibly limiting the availability of nutrients. The following season, there was much more rainfall throughout the season (Fig. 4.1) and the plots did not experience a lack of flowering. Similar conclusions were found by Gigou et al. (2009) at a field site with similar rainfall and soil parameters that fertilizer had less effect on total above ground biomass when water was limiting. In the 2022 field season, the fertilized plots flowered and produced grain, but an increase of biomass did not correlate to an increase of grain yield.

Grain yields may be impacted by the challenge of harvesting and processing fonio grains. Overall grain yields (0-260 kg/ha) in both seasons were extremely low especially compared to yields in West Africa (275-1175 kg/ha) (Figure 1.1). Fonio is known to shatter at grain maturity (Bakare, 2005; Cruz et al., 2016). During both field seasons, grain matured at different rates, so a plot was harvested when the majority was at grain maturity. However, there is a possibility that grain was lost due to shattering and plots were harvested outside of peak grain maturity. There were also challenges with separating fonio grains from other weed seeds. The size of fonio grains is similar to amaranth and many other common weeds meaning that fonio grain was challenging to separate by sieving or by weight. This may lead to inflated fonio grain yield measurements and possibly greater grain yields in plots with more weeds. Future studies may prevent these challenges by more tedious removal of weeds from the plots or an effort to harvest fonio seed heads before cutting for biomass yield. Learning from West African producers may have also aided in the process but was not feasible for this study. There may also be opportunities to learn and adapt mechanized processes from U.S. farmers who process comparable seed.

Forage Potential

The potential of fonio as a forage crop in the United States and elsewhere, depends on the quality of the stover and the biomass yield. In this study, we assessed forage quality at different cuts in the seeding rate study and measured the dry biomass. During the first season, at optimal forage quality, fonio forage had higher quality and crude protein compared to small grains, annual ryegrass, orchard grass, Bahia grass, Bermuda grass, pearl millet, sorghum, and peanut vines (*UGA Cooperative Extension*). Forage quality was only lower compared to legumes and alfalfa, but yields were low at 1236 kg/ha (0.5 tons/acre). In the second field season, quality was comparable to alfalfa forage quality with an RFQ of 151, but much lower yields 470 kg/ha (0.19 tons/acre). According to the USDA, forage yields for annual summer grasses such as millets and crabgrass are on average between 4-8 tons/acre. Forage yields of fonio in both years were well below the average for summer grasses. However, compared to other annuals grown in Michigan, like tef grass and crabgrass, the forage yield was comparable (Fig. 4.6).

We also assessed forage yield and quality at grain harvest, the highest forage yield potential. In the first year, the second cut was comparable in quality to other grasses according to *UGA Cooperative Extension* with RFQ of 121, and yields were higher at 5585 kg/ha (2.26 tons/acre). In the second field season, forage quality (RFQ= 118) and yield were lower-2249kg/ha (0.91 tons/acre). The difference between years is unexpected since year 2 had greater rainfall (Fig.1) and was planted earlier. In the second year, a recut (cut 3) was also taken of the original first cut to test the possibility of cutting fonio twice for forage. The recut had lower yield than the second cut but higher quality. Total yield for two cuts (1 cut at booting stage and a recut at grain maturity) was 2718 kg/ha (1.1 ton/acre) which is low compared to other summer grasses, but comparable to summer annuals grown in Michigan.

We hypothesized that seeding rate would increase forage yields but found that forage yield and quality were unaffected by seeding rate. These results are similar  to spring oat grown for forage in the central great plains where seeding rate did not affect forage yield or quality (Obour et al., 2019). Forage sorghum demonstrated that an increase of seeding rate decreased stalk thickness and improved quality but did not having an effect on forage yield (Mekasha et al., 2022). It may be concluded that forage yield is not affected by seeding rate, but plant partitioning at higher levels of competition may affect forage quality. For fonio forage production, low seeding rates are acceptable. The five varieties tested demonstrated that variety may influence forage yield, quality, and the potential for multiple cuts. The varieties yielded 544-791 kg/ha (0.22-0.32 ton/acre) in the first cut and 2820-4890 kg/ha (1.14-1.98 ton/acre) in the second cut. These variety trials were unreplicated over a single field season, so more robust variety trials are needed to determine varieties with optimal qualities for forage yield and quality.

Fonio being a high quality, but low yielding forage crop has multiple implications for farmers globally. In West Africa, fonio is used both as a forage crop and as a grain crop for animals (C. I. Ukim et al., 2021). As a dual use crop for grain and hay or forage, fonio may have increased economic benefit for farmers. Fonio can be grazed or cut at the booting stage for optimal quality while still producing a grain crop. The leftover hay may also be used for animal feed. As a grazed crop, we still do not know the regrowth potential after grazing or how fonio may perform in a pasture mixture. In the U.S., fonio may be grown as a second crop and benefit farmers since it has low nutrient requirement and quick maturing varieties. These are the first forage quality assessments. Forage quality measurements are needed across varieties which may inform breeding efforts to improve the forage yield. Yield will need improvement to better compare with summer annuals if fonio is to be grown globally as a forage crop.

Management Recommendations

Based on these studies there may be different management strategies based on the intended end use for biomass or grain yields. There were no interactions between a low and high seeding rate and a zero or low fertilizer rate. The only fonio yield affected by fertilizer and seeding rate was above ground biomass, which increased by seeding rate, but only increased by fertilizer at higher planting densities, indicating that farmers may benefit less from fertilizer when fonio is planted at low rates. There was also no corresponding increase in grain yield which is contrary to the correlation between fonio biomass and grain yield established by Amekli (2013) but may be impacted by the challenges previously stated in collecting grain yields. More field seasons are needed to verify these results, but these preliminary findings support that farmers may not benefit from fertilizing fonio sown at low rates and sowing fertilizer at a high rate may increase above ground biomass but may not increase grain yield. We recommend that when growing fonio for grain, low seeding rates be used with no fertilization and when growing fonio for forage, high seeding rates be used with low amounts of fertilization.

## 4.6 Conclusion

The purpose of this research was to characterize several fonio varieties' growth and forage potential in Michigan and begin studying the effect of fertilizer and seeding rates on yields. There are many challenges associated with growing fonio in a new environment including: lack of flowering, weed pressure, and grain harvest and purity. Our findings suggest that fonio may be planted at low seeding rates with zero or low fertilizer inputs. Higher seeding rates may benefit from low amounts of fertilizer especially for better aboveground biomass. As a forage, fonio is high in quality and may be cut several times during the growing season but has much lower biomass yield compared to other annual grasses. Preliminary variety trials indicate that forage quality, biomass yield, and regrowth ability may be affected by variety. Further research on fonio is needed to better understand its potential as a cover crop or forage mixture in U.S. agricultural systems.

# 5. CONCLUSIONS

Increased biodiversity greatly benefits agroecosystems by improving function and stability over time. Management for resiliency is especially needed as climate change puts more strain on production. Minor crops offer a resource to fill niches where major crops cannot and an opportunity to increase diversity. Fonio may be one of these crops to contribute to global diversity and may fill a niche as a drought tolerant, adaptable, nutritious small grain for human and animal consumption. There is little known about fonio production beyond the West African context and research on fonio had not yet been synthesized to find major gaps in knowledge.

The interdisciplinary scoping literature review revealed areas with little research and how that research may benefit other disciplines, leading to insights for innovation. There are major gaps in our knowledge of production, specifically in breeding and improved production practices. While several management practices have been tested, such as planting date, fertilization, and sowing method, these studies have not yet been tested across varieties or environments. Mechanization of processing may also benefit producers by reducing the labor needed to prepare the grain for consumption. Breeding programs will also benefit producers by reducing the amount of shattering and grain loss which occurs during harvest. There is abundant opportunity to increase the market for fonio products especially in urban areas, but first, production must increase to support the growing demand.

To test fonio production in a new environment, the field study documented growth of fonio in Western Michigan, laying the foundation for growing fonio in the Midwest and identifying how specific management practices may affect fonio growth and yields. The study found that low seeding rates and low fertilization improved total biomass yields and had little to no effect on grain yield. Relative forage quality was high (130-150) when cut for optimal forage quality, but yields were low (2249-5585 kg/ha) compared to alfalfa and clover. Fonio may be cut several times for forage, but quality is reduced with subsequent cuttings. From these trials, it can be concluded that fonio may be grown with relatively few inputs but would benefit from breeding to improve forage yields. The trials also emphasized several challenges with growing fonio in Michigan. Growing fonio as a grain crop may be challenging due to inconsistent flowering and grain processing challenges. More research will also be needed to test the resistance of fonio to drought since this is widely accepted, but not necessarily confirmed in our trials. Further research may test specific niches for fonio in U.S. cropping systems.

The next steps in fonio research must be to support increased production and breeding programs with a specific focus on improving fonio for West African producers. A breeding program to help reduce grain loss such as shattering, and lodging is most likely the first step in varietal improvement. Increasing grain size may also improve yields but may affect other factors such as grain quality and storability. New varieties must also be tested across many agroecosystems, even globally. More research could benefit U.S. cropping systems by finding niches for fonio and increasing total number of crops grown per region. As research continues, every effort must be made to empower fonio producers and support the cultural value of fonio. In breeding, this looks like continued evaluation of farmer and consumer needs. Greater documentation of fonio consumption is needed throughout West Africa. Participatory breeding may also produce valuable insights from farmers and aid in adoption. Continued strengthening of seed systems can help preserve genetic diversity of fonio and disseminate improved varieties. When technologies are shared among farmers, programs must intentionally give opportunity for historically disempowered farmers to participate. When marketing fonio in new global markets or as new products, researchers, and consumers can play a part in responsible use of genetic resources and products. Bottom-up regulation from farmers through collective action or NGO’s may also help protect fonio producers.

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