





REVIEW

Enset-based agricultural systems in Ethiopia: A systematic review of production trends, agronomy, processing and the wider food security applications of a neglected banana relative

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Societal Impact Statement

Enset is a staple food for over 20 million people via its starch-rich corm and pseudostem, yet it is virtually unknown outside a narrow zone of cultivation in southern Ethiopia. Due to acculturation and urbanization coupled with climate change, emerging pests and the introduction of new crops, the extensive indigenous knowledge associated with this crop is in danger of being lost, imperilling the future food security and prosperity of millions of Ethiopians. Here, we synthesize the current state of enset ethnobotanical research, identifying key gaps and challenges, and provide a framework for further enset research to safeguard this important, but neglected, tropical crop.

Summary

Enset (*Ensete ventricosum* (Welw.) Cheesman) is the major starch staple of the Ethiopian Highlands, where its unique attributes enhance the food security of approximately 20 million people and have earned it the title "The Tree Against Hunger". Yet enset-based agriculture is virtually unknown outside of its narrow zone of cultivation, despite growing wild across much of East and Southern Africa. Here, we review historical production data to show that the area of land under enset production in Ethiopia has reportedly increased 46% in two decades, whilst yield increased 12-fold over the same period, making enset the second most produced crop species in Ethiopia—though we critically evaluate potential issues with these data. Furthermore, we address a major challenge in the development and wider cultivation of enset, by reviewing and synthesizing the complex and fragmented agronomic and ethnobotanic knowledge associated with this species; including farming systems, processing methods, products, medicinal uses and cultural importance. Finally, we provide a framework to improve the quality, consistency and comparability of data collected across culturally diverse enset-based agricultural systems to enhanced sustainable

*This article is dedicated to the memory of our colleague and friend Dr Mark Goodwin.

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use of this neglected starch staple. In conclusion, we discuss the challenges and opportunities for enset cultivation beyond its restricted distribution, and the regional food security potential it could afford smallholders elsewhere in Southern and East Africa.

KEYWORDS

agricultural systems, agroforestry, crop wild relative, food security, home gardens, indigenous knowledge, medicinal use, sustainable agriculture, tropical crop ecology

1 | INTRODUCTION

Ethiopia is ranked 104th of 119 countries in the most recent Global Hunger Index (von Grebmer et al., 2017), with 28.8% of the population undernourished from 2014–16. The national costs of malnutrition have been estimated at US\$ 4.7 billion annually, with significant long-term socio-economic consequences (African Union Commission World Food Programme United Nations Economic Commission for Africa, 2012). Despite being a center of diversity and domestication for food crops, Ethiopia has been the largest recipient of targeted food aid (World Food Programme, 2013). Ethiopia's agricultural history is characterized by the domestication of cultigens including coffee (*Coffea arabica* L.), tef (*Eragrostis tef* (Zuccagni) Trotter), khat (*Catha edulis* Forsk), noog (*Guizotia abyssinica* (L.f.) Cass.), finger millet (*Eleusine coracana* L.) and enset (*Ensete ventricosum* (Welw.) Cheesman) (Harlan, 1969, 1971; Khoury et al., 2016). Whilst coffee has become one of the most highly traded global commodity crops (Ponte, 2002), and others have widespread and growing international importance (e.g., tef, [Cheng, Mayes, Dalle, Demissew, & Massawe, 2017]), enset has remained largely overlooked. It is perhaps the only major

Ethiopian domesticated crop that has never been cultivated outside Ethiopia, despite wild populations of *E. ventricosum* occurring from Ethiopia, and eastern DR Congo (along the rift valley mountain ranges) to South Africa (Figure 1). This highly localized cultivation (though by many socio-cultural and ethnolinguistic groups) may in part explain limited research to date, despite indications that enset could play a key role in meeting food security challenges (Brandt et al., 1997), not only in Ethiopia, but also further afield.

Enset (*Ensete ventricosum*, Musaceae), is an unusual crop/plant from a sister genus to the bananas (*Musa*). Enset differs from domesticated bananas in that the mature plant does not produce edible fruit (these are filled with numerous large and hard seeds, similar to many other wild banana species). Instead the plant is grown for 3–12 years, before the pseudostem and corm are harvested and collectively processed into starchy food products (Shack, 1966). Enset serves as a staple food for about 20% of the Ethiopian population, over 20 million people, mainly in the south and south-west of the country (Borrell et al., 2018). Under appropriate conditions it is estimated that 60 mature plants can provide enough food for a family of five to six people, over the course of a year, when consumed with other dietary components; typically meat, dairy, and cabbage (Demeke, 1986).

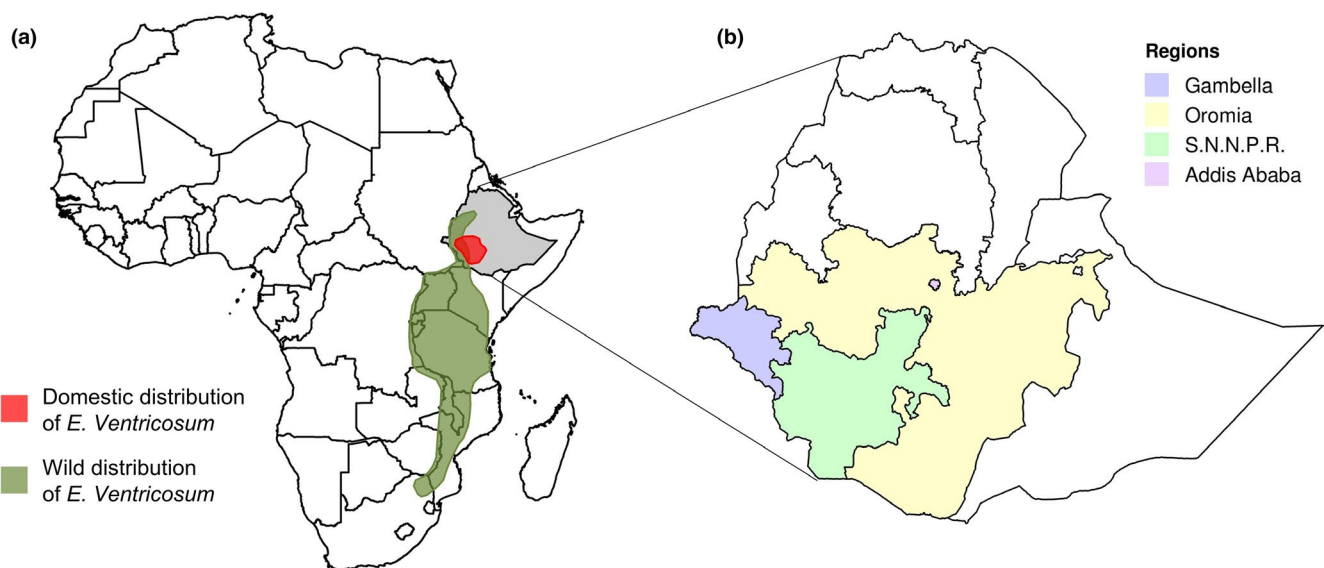


FIGURE 1 (a) The distribution of wild and domestic enset in Eastern and Southern Africa. It should be noted that domestic enset displays a range expansion east towards and across the Ethiopian rift valley system, beyond the current distribution of wild enset; (b) inset Ethiopia with the main study areas discussed in this article

Enset farming systems contribute to the long-term sustainability of food production through several mechanisms. Enset is perceived to be relatively tolerant of drought (Garedew, Ayiza, Haile, & Kasaye, 2017; Zerfu, Gebre, Berecha, & Getahun, 2018), withstand heavy rain, tolerate flooding, and endure frost damage (Degu & Workayehu, 1990). Enset can be harvested at any time during the year, be harvested at any growth stage over a period of several years (up to an including the early flowering stage), and the fermented products can be stored for long periods (Brandt et al., 1997; Garedew et al., 2017; Sahle, Yeshitela, & Saito, 2018). This combination of characteristics gives enset an important role during times of famine in the areas in which it is traditionally cultivated. Enset's resilience and versatility has earned it the name 'The Tree Against Hunger' (Brandt et al., 1997) and it already forms the basis of many households' food security (Negash & Niehof, 2004; Sahle et al., 2018).

We consider that there are two major challenges for the improvement of existing enset farming practices and the adoption of enset-based agriculture outside of the current distribution in south west Ethiopia. The first, is poor characterization of ecological requirements, genetic diversity, and the impact of changing climate, recently reviewed in a companion paper by Borrell et al., (2018). The second, addressed here, is poor documentation of the extensive ethnobotanical knowledge and practices associated with enset cultivation and recent enset household production trends in

a national context. Smallholders account for 96% of the cultivated area in Ethiopia (Taffesse, Dorosh, & Gemessa, 2013), with at least 48 ethnic groups native to the Southern Nations, Nationalities and Peoples Region (the major enset growing region), 88 recorded languages (Population Census Commission, 2007) belonging to four major groups (Omotic, Semitic Nilotic, and Cushtic) and a corresponding multitude of ethnobotanic practices. Therefore, here we investigate and summarize reported uses and management of enset, recent trends in cultivation, emerging by-products and opportunities for improvement. We hope that by providing a framework within which to report enset ethnobotanic research, we can enable and catalyse development of this important Ethiopian food security crop.

1.1 | National production and yield trends

Analysis of data from Ethiopia's Central Statistics Agency (CSA, 1995–2017), shows the area of land under enset production has increased approximately 46% over the past twenty years, whilst yield has been reported to increase twelve-fold (Figure 2; Dataset S1; see Methods in Supporting Information), implying substantial productivity improvements. We have concerns over the validity of these data for several reasons. First, these data are at odds with several studies reporting that farmers perceive enset production to be declining (Abebe, 2013; Negash, 2001; Yemataw et al., 2017; Zippel, 2005).

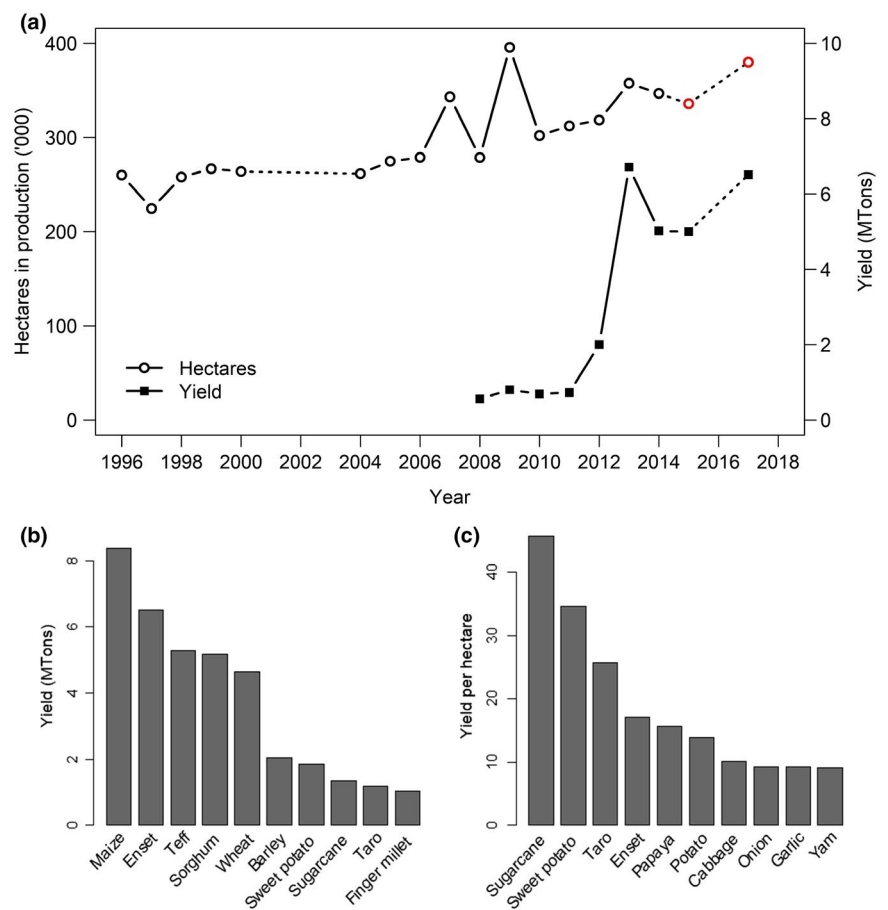


FIGURE 2 Enset agriculture in Ethiopia, showing (a) hectares in production (circles) and yield (squares). Dashed lines indicate interpolation between incomplete data. Red circles denote values based on incomplete reported data. Yield data is not available prior to 2008. All data sourced from the Central Statistics Agency Agricultural Sample Survey (1996–2018); (b) national yield for the ten highest yielding crops in Ethiopia (2017–18); and (c) yield per hectare for the ten most widely produced crops (2017–18). Enset ranks second in yield per hectare and is the fourth highest yielding crop per hectare

Second, over a similar period, (1996–2017) the Ethiopian population increased 77% from 59 to 105 million (Center for International Earth Science Information Network, 2017). This disparity could be partly attributed to a proportional reduction of enset land area per person, as enset agriculture fails to keep pace with population growth, however, this is unlikely to be the case for overall yield. Third, there appears to be little evidence for policy or crop development-based drivers that could have contributed to the reported productivity increase. Instead Cochrane and Bekele (2018) report undocumented 'methodological changes' at the Central Statistics Agency and highlight concerns over quality, methods and politicization of the data, with inconsistencies over several other tuber crops such as taro and sweet potato.

A final pervasive source of error in estimating enset yield is the difficulty in applying agricultural survey methods developed for annual or perennial crops (e.g., cereals) to enset, a multi-year crop, where the intermediate stages can be harvested, harvesting ends the life of an individual enset plant (unlike perennial crops that continue producing yearly after the initial harvest) and complex transplanting strategies frequently alter the number of plants per hectare (summarized in Box 1). More recent surveys (2012–17) (Central Statistics Agency, n.d.) have employed an approach where the number of plants harvested is recorded, and this is multiplied by the anticipated yield of food products (mainly *kocho*, *bullā* and *amicho*, see below) per plant. However, the time lag between planting and harvesting (4–10 years, depending on the local conditions and management efficiency), may result in data artefacts; for example overharvesting (harvesting enset at a faster rate than enset plants are replenished) could give the temporary impression of increased production, whilst the overall hectareage declines, unless rigorous survey methods are employed. Thus an empirical evaluation of hectares in production, the number of harvested plants and overall yield is key to monitoring enset's role in providing food security.

Yield assessments for 2017/18 report that enset was the second most produced crop species in Ethiopia, with the fourth highest yield per hectare (Figure 2), highlighting its importance to Ethiopian agriculture (Central Statistics Agency, n.d.). Nevertheless, estimates of enset yield (per-plant and per-hectare) in the literature vary substantially (Table 1). Whilst much of this variation can be attributed to the challenges in surveying enset outlined previously (Box 1), there are also important differences in enset cultivation density and yield in different regions, likely attributable to local agroecological conditions (Shank & Ertiro, 1996). For example, lowland parts of the Gurage region are typically drier than other enset growing areas and this may be a contributing factor to it having one of the lowest enset planting densities, reducing competition between plants (Sahle et al., 2018) (see Table 1). In the same study, the authors show annual yields per hectare can vary from 2.9–7.7 tons when compared across local agroecological zones. Pijls, Timmer, Wolde-Gebriel, and West (1995), based on another survey in the Gurage region, measured the energy yield per area and unit of time for enset as 1,450 kcal/m² per year, substantially higher than that of other common Ethiopian staples such as cereals, potato, sweet potato and banana. Therefore, when considered per unit of space and time, in some localities enset earns the title of most efficient Ethiopian crop (Tsegaye & Struik,

Box 1 Challenges and sources of variation in estimating area under production and yield for enset agriculture in Ethiopia

Estimating hectares under production

- Transplanting occurs up to five times, at increasing spacing meaning that enset density varies with age class.
- Final mature spacing differs in different regions, potentially dependent on variables such as precipitation and soil moisture.
- Enset is sometimes intercropped with other food or cash crops such as coffee (*Coffea arabica*); in some areas such as Gedeo and Sidama, enset is also grown in the understory of agroforestry systems.
- Enset is harvested most frequently at 4–6 years old, but may be harvested from as little as 2 years, until flowering, which may be 12 years in some conditions.
- A variable portion of total enset hectareage (often 15%–25%) harvested each year, depending on household requirements and performance of other crops.
- Annual mortality, including impact of pests and diseases is poorly known.

Estimating yield

- Yield varies due to varying performance in highly heterogeneous agroecological conditions across the crops' distribution.
- Yield likely varies due to differing performance of genetically distinct landraces.
- Yield varies based on age at harvest.
- Yield per hectare sometimes comprises a hectare of harvested enset, or alternatively the yield of enset that can be sustainably removed from a hectare each year (for example, ~1/6th of the total area).
- Yield and ratio of different food products (*kocho*, *bullā* and *amicho*) vary depending on cultivated landrace.
- The number of plants harvested and yield may be withheld or misreported.
- Water content of derived products rarely quantified.
- Local unit names and weights for enset products also vary, even across small spatial scales (e.g. neighbouring communities).

2001). Despite this reputation, continuing to develop higher enset yields remains a key focus for Ethiopia's agricultural system as asserted by Taffesse et al. (2013) and many other researchers.

1.2 | Regional importance

The prevalence of enset agriculture across Ethiopia is highly heterogeneous, depending on both amenable agroecological conditions and

TABLE 1 Enset yield per plant, yield, and number of plants per hectare reported in the literature

Estimate	Notes	References
<i>Yield per plant</i>		
30.5 kg	Author also reported subaverages of 30, 34, and 27 kg, in Endebir, Kambata and Sidama districts respectively.	Makiso (1975)
25 kg	—	Ashagari (1984)
27 kg	Kocho only, (30 kg total yield)	Alemu and Sandford (1991)
30.8 (±9.3) kg	Encompasses measurements across 20 woredas in five zones.	Evans (1993)
34 kg	Kocho only	Pijls et al. (1995)
39.2 kg	Authors also report a range of 12–100 kg across all samples.	Shank and Ertiro (1996)
8–70 kg		Tabogie (1997)
16–37 kg	Author also noted an average harvest of 19 kg bulla	Tsegaye (2002)
52 kg	Kocho at 40% dry matter	Zappacosta, Robinson, Edirisinghe, & Ronchini (2007)
15–61 kg	Unsqueezed (wet weight)	Shumbulo et al. (2012)
20 kg	Dry weight	Bill and Melinda Gates Foundation (2014)
50.3 kg	Consisting of 27 kg Kocho, 23 kg amicho and 1 kg bulla	Central Statistics Agency (2013–17)
16.2 (±7) kg	These data included all plant sizes on the farm, encompassing those too small to normally be harvested.	Sahle et al. (2018)
<i>Yield per hectare</i>		
2.4 t	National estimate	Central Statistics Office 1968 (sourced from Pijls et al., 1995)
3.3–7 t	Study undertaken in Wolayta zone	Wolayta Agricultural Development Unit 1978 (sourced from Shank & Ertiro, 1996)
8.3 t	—	Ashagari (1984)
6.6–23 t	National estimate (50% moisture content)	Alemu and Sandford (1991)
9.5 t	Study undertaken in Gurage zone	Pijls et al. (1995)
10.8 t	Derived from six smaller unreported studies.	Chiche (1995)
10–12 t	Study reported use of N, P and K fertilizer, with yields 3–4 times lower without fertilizer application.	Ulolo and Mengel (1996)
21.7 t	National estimate	Central Statistics Agency (2008–11 mean)
147.7 t	National estimate	Central Statistics Agency (2012–17 mean)
6.5 (±0.3) t	Study undertaken in Gurage zone	Sahle et al. (2018)
<i>Plants per hectare</i>		
2,300	—	Alemu and Sandford (1991)
2,500	Based on 2 m × 2 m plant spacing	Zappacosta et al. (2007)
10,000	—	Shumbulo et al. (2012)
2,222	Based on plant spacing of 1.5 m × 3 m	Gates Foundation (2014)
1,024 ± 89	Empirical field measurements using 10 m × 10 m plots	Sahle et al. (2018)

local cultural preferences. Enset is most abundant in northern and eastern zones of the Southern Nations, Nationalities and Peoples Region (SNNPR), but is also an important crop in Oromia and parts of eastern Gambela. Figure 3 presents current yield across enset producing districts (*woredas*), and recent trends in the land area under enset agriculture from the period 1997–2014 (the most recent data available by district; see Dataset S2 and Methods in Supporting Information).

1.3 | Household utilization, supply and demand

Household utilization of enset (available CSA data averaged for the period 2008–16) also indicates its important role in household food security, with enset having the highest consumption rate for both humans and livestock, the most used crop for ‘wages in kind’ and the lowest sale rate (Figure 4). It is perhaps due to this high degree of

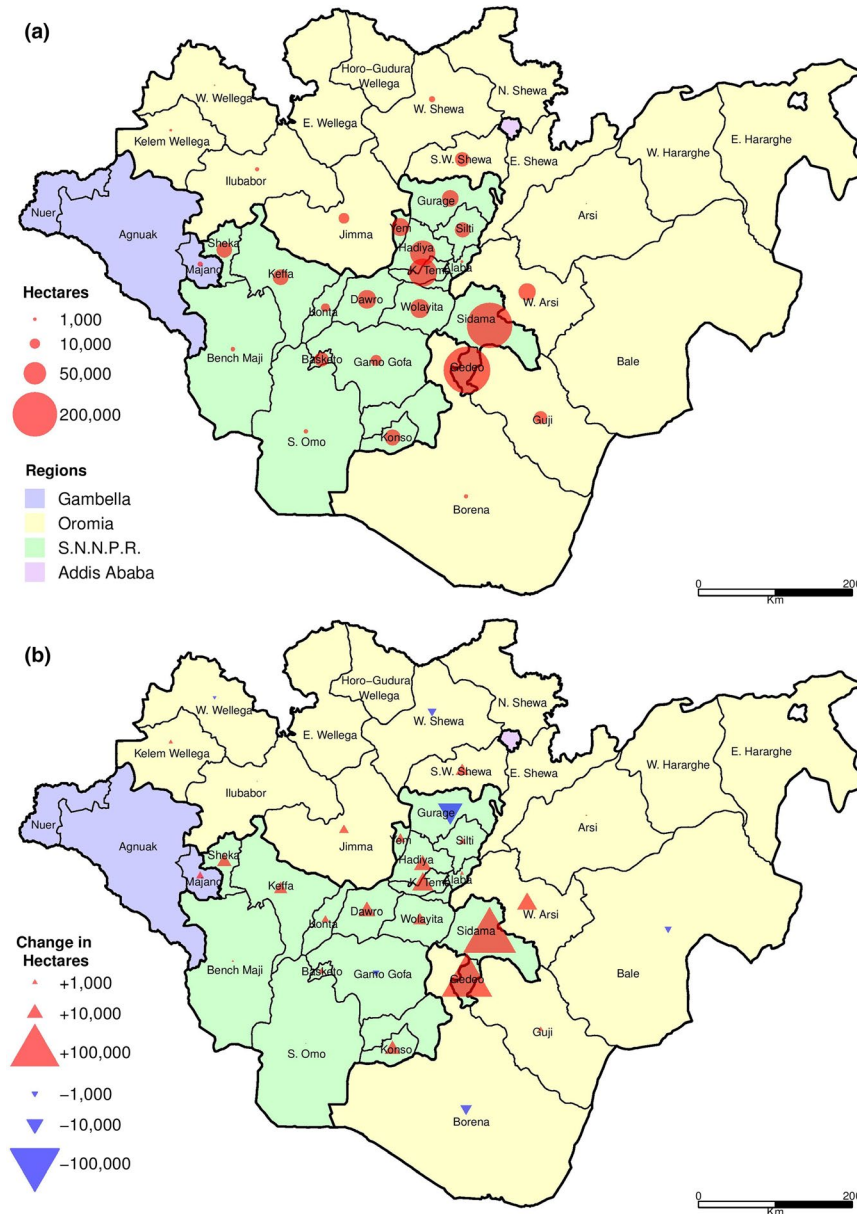


FIGURE 3 The major enset-producing areas in South and South-west Ethiopia. (a) Area under enset production (hectares) for the year 2014 (the most recent data available at zonal level); (b) trends in the area under enset production for the period 1997–2014

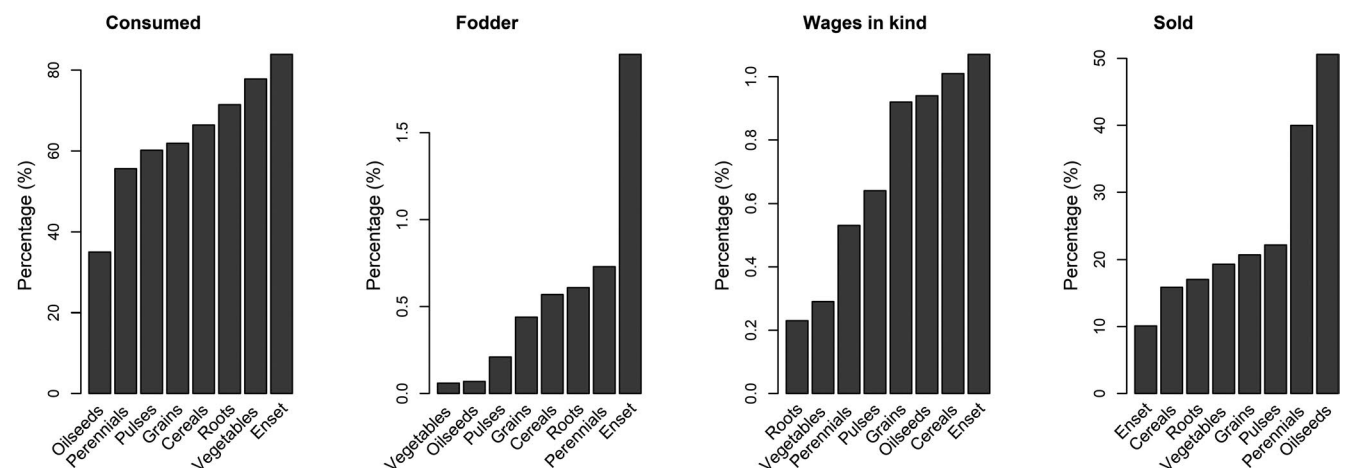


FIGURE 4 Enset household percentage utilization, with data averaged over the period 2008–2015. Perennial crops exclude enset

household use that, unlike cereal crops, trends in the market price of enset products are poorly known. Although a recent study by Sahle et al. (2018) mapped supply and demand for *kocho* in the Wabe River catchment of the Gurage Mountains in southern Ethiopia (Gurage zone, SNNPR). Here, the average *kocho* demand per person was met by 16 plants, which is consistent with Demeke (Demeke, 1986). Sahle et al. (2018) did, however, note that only 38% of households can meet demand from home gardens. There was a good supply of *kocho* in most areas, but demand exceeded supply in 25% of the catchment.

2 | ENSET AGRONOMY AND FARMING SYSTEMS

2.1 | Propagation and tissue culture

Domesticated enset is exclusively propagated vegetatively using suckers from the appropriately prepared corm of a young plant. As enset plants are generally harvested before full emergence of the inflorescence, seeds are rarely available to farmers, although preference for vegetative reproduction is normally attributed to the increased vigor of the suckers/plantlets (Alemu & Sandford, 1991). There is a single domesticated enset landrace from the Ari region, known to spontaneously sucker from the leaf petiole base. Enset seeds from cultivated landraces are characterized by low germination rates (Negash, 2001), while higher germination rates have been observed for wild enset (Z. Yemataw, pers. comm.). Wild enset is assumed to reproduce exclusively via seeds, because spontaneous suckering has not been observed.

Suckers initiate from growing buds found in concentric circles on the upper section of the corm. While some variation in corm preparation are reported between different ethnic groups (Diro, Haile, & Tabogie, 1996) the principal aspects are consistent. To produce suckers for planting, a farmer will harvest the pseudostem and save the corm of a desired plant to initiate suckers. In contrast to banana, naturally occurring sucker production is rare due to the very high dominance of the apical meristem, which must be destroyed/removed to stimulate sucker production. After the removal of the apical meristem, corms are kept in its entirety or are split into two or four equal parts. After preparation, the corm/corm pieces are planted 20–30 cm deep in loosened soil, mixed with manure. Corms from plants of 2–4 years old and about 10–35 cm in diameter are preferred (Bezuneh & Feleke, 1966; Yemataw, Mohamed, Diro, Addis, & Blomme, 2014). Each corm (piece) will produce between 40 and 200 suckers, depending on the cultivar, size and age of the mother plant, soil characteristics, rainfall, land preparation and time of planting (Shumbulo, Gecho, & Tora, 2012). Suckers appear 2–3 months after planting (Tsegaye & Struik, 2002). Time to sucker emergence is shorter for split corms and a higher number of seedlings are generated this way compared with entire corms (Karlsson, Dalbato, Tamado, & Mikias, 2015). Early emergence is associated with more vigorous suckers, which promotes success of establishment, higher and earlier

yield (Tabogie & Diro, 1992). In areas where extended droughts are common and watering is difficult, it may be preferable to use whole corms to reduce corm desiccation; in other areas watering and application of manure is advised (Karlsson et al., 2015).

Various technologies have been developed to increase sucker production (Yemataw, Tawle, Blomme, & Jacobsen, 2018). Makiso (1996) refers to a macro-propagation method to regenerate enset plants by cutting the corm, with leaf bases intact, vertically into small pieces which are then planted in plastic tubes or bags and raised in a growth chamber with proper temperature and humidity (20°C and moist medium of soil or any other material). Other rapid propagation methods have been reported by Diro, van Staden, and Bornman (2004), including zygotic embryo culture (Bezuneh, 1980; Diro, van Staden, & Bornman, 2003; Negash, 2001; Negash, Puite, Schaart, Visser, & Krens, 2000), shoot tip culture (Afza, van Duren, & Mopurgo, 1996; Negash et al., 2000; Zeweldu, 1997), and callus culture and somatic embryogenesis (Mathew, Manuel, & Philip, 2000; Mathew & Philip, 2003). Micro-propagated enset plants are prone to various issues, including blackening resulting from phenolic oxidation of explants, necrosis and the formation of unwanted callus. Low levels of multiple shoot formation are also observed from shoot tip explants (Diro et al., 2004), thus these approaches do not yet provide an alternative to sucker propagation.

2.2 | Transplanting and harvest

Harvested suckers are planted in a nursery plot (0.5 to 1 m² plant⁻¹) where they grow for about one year. Subsequently, suckers are consecutively transplanted into ever more widely spaced arrangements, with a final minimal spacing of 2 to 4 m² plant⁻¹ (Bezuneh & Feleke, 1966; Hiebsch, 1996; Tsegaye & Struik, 2002), with wider spacing more common in areas of lower soil moisture e.g., Gurage (Sahle et al., 2018; Table 1). Since the corm and pseudostem are harvested, higher yields can be expected by successive transplanting steps which delay flowering, thus allowing a longer period of time for vegetative growth, which includes assimilation of starch in the pseudostem and corm. Therefore, direct transplanting is advised when early yields are the objective, but more frequent transplanting will result in higher yields per plant (Tsegaye & Struik, 2000). Once equilibrium (planting = harvesting) has been achieved, annual yields will be higher for twice transplanted plants compared to once transplanted as this encourages greater partitioning of dry matter to the harvestable parts (Blomme, Jacobsen, Tawle, & Yemataw, 2018; Tsegaye, 2007). Systems involving up to five transplanting stages are used in some areas (J. Borrell, pers. obs.). An additional benefit of repeated transplanting is the smaller overall space required (i.e., all plots with varying plant size/density are grown together). Full maturity of the enset plant is reached after 4 to 12 years, depending on the landrace and altitude of the farm, with higher locations significantly increasing cropping cycle duration (Negash, 2001). The ideal moment to harvest is at inflorescence emergence. At that time, dry matter yield is highest. After flowering, assimilates are redirected toward the inflorescence

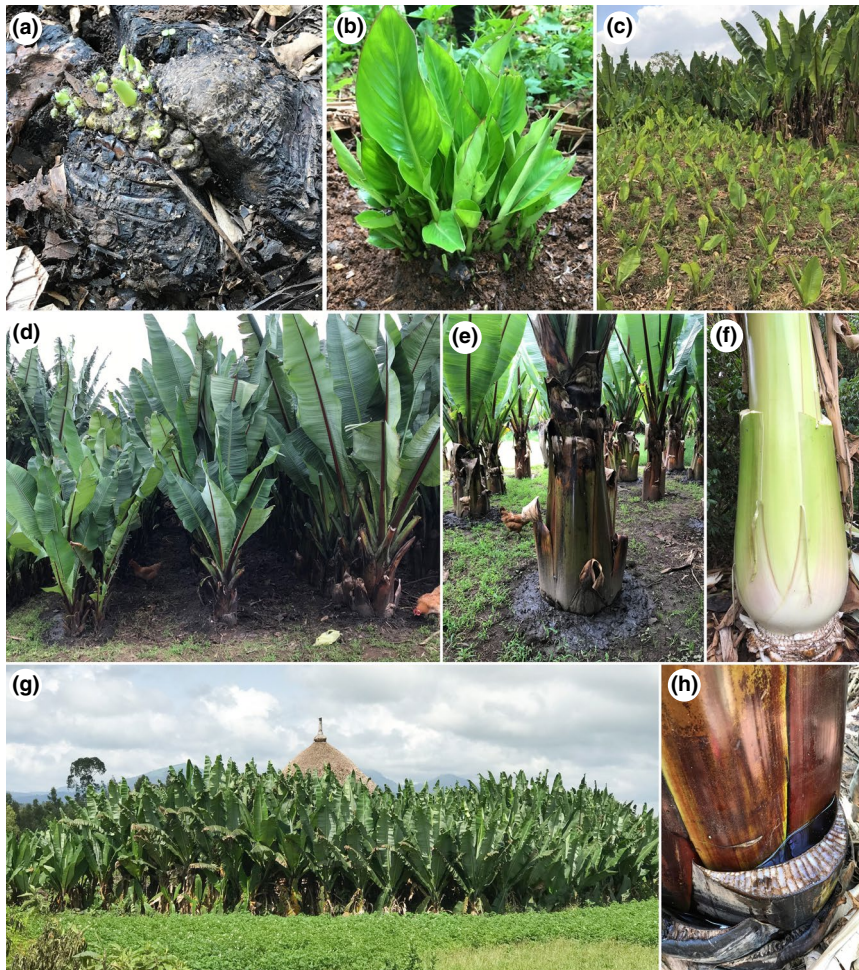


FIGURE 5 (a and b) Enset corm with newly emerging shoots; (c) young enset plantlets at second transplanting stage. Spacing and number of transplanting stages varies across different regions; (d) 2–4-year-old plants at second and third transplanting stages; (e) wider spacing at final transplanting stage, with fresh application of manure; (f) mature enset with dry leaf sheaths removed, ready for harvesting. Upper portion of the corm, with roots removed is also visible; (g) traditional hut in Hadiya Zone surrounded by enset; and (h) enset leaf sheaths appear adapted to store water, here water is observed over a month since the last substantial rain

and away from the pseudostem and corm (Tsegaye & Struik, 2000). A summary of growth stages is presented in Figure 5.

2.3 | Enset farm management and fertilization

As a perennial crop enset fields generally do not require tilling (depending on intercropping practices), though sequentially spaced and sized holes are dug for subsequent transplanting stages and then reused for successive individuals. Due to large leaf surfaces rainfall is intercepted, limiting erosion. Enset leaf bases also appear to be adapted to trap water close to the pseudostem, with pools of water observed even several months into the dry season (Figure 5h; J. Borrell, pers. obs.). Irrigation practices have not been observed. Enset appears to have a larger root system and thicker root cords compared to banana (possibly aiding plant stability in its preferred natural habitat of steep riverbanks and slopes), with 89%–96% of roots in the upper 40 cm soil layer (Blomme, Sebuwufu, Addis, & Turyagyenda, 2008). Enset leaves and discarded parts of the pseudostem are frequently used as a mulch, which enhances soil moisture and organic matter.

Enset farming systems are reported to require relatively little off-farm input, however manure application is widespread and considered essential by enset farmers. Manure is derived

from livestock which are traditionally housed immediately adjacent to the enset for ease of transfer. As a result soil fertility in enset fields is reported to be greater than in surrounding fields or pastures (Shank & Ertiro, 1996). The rate, timing, and method of manure application varies among households and depends on the growth stage of the plantation and the availability of manure (Tsegaye & Struik, 2002).

Compared to other crops, there are very few fertilizer response trials for enset. Bezuneh (1984) applied 3 kg manure-compost, 500 g N and 400 g P_2O_5 per plant, in an effort to determine the yield potential of enset. Plants were harvested after one transplant and 40 months at 1800–2000 m above sea level and a spacing of 5 m² per plant. Fresh *kocho* weights per plant of 18.5, 22.2 and 29.8 kg respectively for the landraces “Ferezae”, “Tuzuma” and “Adow” were achieved, however control comparisons were not reported. Uloro and Mengel (1996) applied 100 kg/ha N and 100 kg/ha P fertilizer, reportedly improving general plant appearance, plant above-ground growth, fresh biomass and fresh rhizome yield of enset in soils which were low to medium in their nutrient status. Inclusion of 200 kg/ha K in the fertilization program further improved plant morphology and rhizome starch production, although K did not have a noticeable effect on above ground biomass yield. Fertilizer application gave dry weight starch

yields in the range of 10–12 t/ha, which is three to four times higher than without fertilizer application.

2.4 | Enset agrisystems

Enset-based agriculture is considered one of the most sustainable of the indigenous farming systems in Ethiopia, with a human carrying capacity higher than other crops and cropping systems for the same agroecology and inputs (Brandt et al., 1997), although further empirical evaluation is necessary. Many enset-based farms are derived from forest, whereby farmers clear away the undergrowth to plant enset, coffee, and other crops, leaving the upper story trees, resulting in multi-story agroforestry systems which are thought to have remained relatively stable for centuries (Kippe, 2002).

Ethiopian agricultural systems are typically highly diverse. Asfaw and Nigatu (1995) identified a total of 162 crop species cultivated throughout the highlands of southern, western, eastern and central Ethiopia. On average, enset farms produce more than 10 different crop and livestock species (Sibhatu, Krishna, & Qaim, 2015), with farmers growing up to 20 different enset landraces within one plantation (Zippel, 2005). With the lowest proportion sold of any Ethiopian crop (Figure 4), cash crops and livestock are integral to enset-based production systems (Kandari, Yadav, Thakur, & Kandari, 2014; Tsegaye, 2002). However, enset does provide a high level of flexibility and security, in that larger enset plants can be sold as a standing plant before being processed or a portion of fermented *kocho* or *bulla* may be taken from the storage pit for sale at any time.

Distinctive enset production systems can be categorized based on environmental, agronomic, and cultural criteria, and the

importance given to enset within each cropping system (Brandt et al., 1997; Shank, 1994; Westphal, 1975), for example enset–coffee–maize is the dominant system of Sidama zone. Additional variation is observed due to wealth of farming households, farming skills, landholding size, availability of resources, access to a highway and altitude (Abebe, 2005). Mellisse, Descheemaeker, Giller, Abebe, and Ven (2018), in an analysis of home gardens, found that overall crop productivity was lowest in the traditional enset–coffee systems (1,820 kg Dry Matter [DM] ha⁻¹) and highest in the newly evolved enset–cereal–vegetable systems (3,020 DM kg ha⁻¹). Energy productivity from food crops was higher in enset-based systems (43 Gigajoules (GJ) ha⁻¹) compared to other systems, but the revenue was lowest in enset-based systems (719 US\$ ha⁻¹) and highest in newly evolved chat-based systems (6,817 US\$ ha⁻¹). Thus many farmers may need to adapt to new agronomic systems and crop combinations that maintain enset's role as a sustainable staple, whilst ensuring sufficient cash crop income.

3 | PROCESSING METHODS, PRODUCTS AND CULTURAL IMPORTANCE

There is considerable variation in the morphological and agronomical properties of enset (Yemataw, Tesfaye, Grant, Studholme, & Chala, 2019), as well as the processing methods in different parts of Ethiopia (see for example Abate, Gebremariam, Hlebsch, & Brandt, 1996; Hunduma & Ashenafi, 2011; Tedla & Abebe, 1994). A number of these practices are illustrated in Figures 5 and 6. The processing of enset is traditionally a role for women, who act as a reservoir of knowledge about the techniques involved, but the tasks involved are



FIGURE 6 (a) Enset midribs used as cattle fodder; (b) young enset plantlets are transported to the market. There is a common assertion that plants originating at higher elevation are more vigorous with less disease, though there is no empirical evidence for this. Damp enset leaf sheaths are used as packaging; (c) enset fiber, known locally as *gantcha*, a by-product of *kocho* preparation; (d) women harvesting enset by scraping the pulp from leaf sheaths in Gurage Zone. *Kocho* and *bulla* are both prepared from this pulp; and (e) a very large *kocho* fermentation pit, Hadiya Zone

labor-intensive and tedious (Hunduma & Ashenafi, 2011). Garedew et al. (2017), in an analysis of the indigenous knowledge of enset management in the Shekicho people of the SNNPR, highlights the danger of indigenous knowledge being lost as younger people turn away from enset-based agriculture, and thus the documentation of the diversity of agronomic practices, and especially processing methods, is a priority.

3.1 | Enset food products

At harvest, starch is decorticated (scraped) from the parenchymatous pseudopetioles forming the pseudostem (consisting of overlapping leaf sheaths), grated and pressed from the corm (the underground base of the stem that serves as a storage organ) and collectively processed, using fermentation pits, into a number of starchy foods. Landraces that yield a white paste of fermented pulp and a white *bulla* are selected for *kocho* or *bulla* production, whilst landraces that produce a friable and sweet corm are selected for *amicho* production. The traditional tools developed for this purpose include: The *watani*, a flat wooden plank against which leaf sheaths are laid for decortication. The *javga*, a wooden tool with a pointed end (crusher) to mash the pseudostem and a serrated end (grater) to pulverize the corm. Finally, the *sibisa*: a split bamboo (scraper) held at both ends and used to scrape the length of the leaf sheath. Names reported are from West Shewa Zone (Oromia).

The most prevalent product is *kocho*, a starch-rich product obtained by fermenting the resulting pulp (from scraping the pseudostem and mashing the corm) wrapped in enset leaves in an underground specially prepared pit within the enset home garden. Crucially there is a perception that fermentation will not be successful or effective if the pit is not positioned within the enset planting area, perhaps indicating shade or temperature are important. The remaining fiber is removed and the resulting paste is baked to make a flatbread with a slightly sour flavor, *kocho*. This flatbread is extremely popular in Ethiopian restaurants and is often served with *kitfo* (raw minced beef mixed with butter and spices). *Bulla* is a by-product of the production of *kocho* and is prepared from the liquid extracted when the scrapings and pulp are squeezed. The starch contained in the liquid is separated out by settling and removal of excess water or by evaporation to produce a white powder that can be stored for long periods. Rehydrated *bulla* can be used in a variety of ways, including making pancakes, dumplings, porridge, soup or a drink. In the SNNPR *bulla* is mixed with seasoned butter and spices to produce small grains that are used much like couscous; whereas, in Western Oromia, *bulla* is mixed with seasoned butter and fresh milk to produce a gelatinous foodstuff. *Amicho* is the fleshy inner portion of the corm, which can be cooked by boiling—much like an Irish potato. *Amicho* tends to be derived from younger plants around three years of age (J. Borrell, pers. Obs.), although there are varieties that are claimed to produce good quality *amicho* even at maturity (e.g., landraces

'Nifo' and 'Zoober'). It is the least commonly encountered preparation method. Similarly, *bulla* is only available in much lower quantities than *kocho*, and is generally more expensive because of the additional processing involved. As a result, a premium price is paid as it is pure starch, with no fiber or other stem-derived materials. The dietary diversity of enset production systems is reviewed in (Jacobsen, Blomme, Tawle, Muzemil, & Yemataw, 2018).

3.2 | Enset fiber and packaging products

Fiber is extracted from the pseudostem and leaves, largely as a by-product of *kocho* production (Figure 6) (Blomme, Yemataw, et al., 2018). The fibers are dried to make sacks, ropes, sieves and mats. The fibers can be 4 m or more in length, depending on the height of the pseudostem, and are strong and flexible. Fiber can also be extracted from the leaf sheath, petioles and midrib, which are commonly used for animal feed, compost and fuel for fires. Teli and Terega (2017) analyzed the characteristics of enset fiber, including tensile strength, elongation at breaking point and thermal stability, and found it to be comparable with many other natural fibers such as abaca, flax, sisal, hemp, and jute. Blomme, Yemataw, et al. (2018) found enset fiber to have a tensile strength of 9.8–17.5 kg g⁻¹ m⁻¹. Enset fiber has the potential to be used for a range of novel applications beyond traditional uses, and there is likely to be variation in performance across genetically diverse landraces.

Enset leaves are used for many purposes, including lining the fermentation pits for *kocho*, wrapping *kocho* and other traditional breads during baking, transporting butter and honey to market, making mattresses and cushions, and as fuel (Tedla & Abebe, 1994). Leaves and dried midribs are also used as thatching for houses and fences, as well as for mulch. It should be noted that wild enset plants are also commonly harvested for these purposes in western regions where both wild and domestic enset co-occur.

3.3 | Animal fodder

A number of authors have analyzed the role of enset as animal feed (Fekadu & Ledin, 1997; Gizachew, Hirpha, Jalata, & Smit, 2002; Nurfeta, Eik, et al., 2008; Nurfeta, Tolera, et al., 2008; Nurfeta, Tolera, Eik, & Sundstøl, 2009) (see Figure 6). Mohammed, Martin, and Laila (2013) identified the leaf as a good source of animal fodder, containing 13% protein, 20% crude fiber and 10% sugar. It is also a good starting material for silage production. There is not enough fiber in the pseudostem to make it a suitable fodder for ruminants, but this problem can be avoided if the remains of the pseudostem, after *kocho* preparation, are mixed with other plant material. The pseudostem, like the leaf blades, contains potassium, magnesium, zinc and manganese in suitable amounts for ruminants, while the calcium levels are not high enough to support the animal and lactation. The pseudostem provides a similar amount of energy to oats and performs similarly to barley in net energy provision for lactation (Mohammed et al., 2013).

3.4 | Nutritional content

Considering the importance of enset as a dietary staple food, compared to other regional crops only a relatively small number of nutritional analyses have been undertaken on raw enset plant tissues (Fanta & Satheesh, 2019; Fekadu & Ledin, 1997; Mohammed et al., 2013; Nurfeta, Eik, et al., 2008), covering a small selection of varieties (max $n = 10$), with a low number of replications (max $n = 3$), summarized in Table 2. Overall, the calorie content of *kocho* per 100 g of edible material is reported 200 kcal or 57% lower than the corresponding value for 100 g of food grains (Urga, Fite, & Biratu, 1996). Other studies have investigated the nutritional value of the resulting enset food products (Atlabachew & Chandravanshi, 2008; Forsido, Rupasinghe, & Astatkie, 2013) or as a component of animal feeds (Afele, 2014; Nurfeta et al., 2009; Talore, 2015). Only one recent paper by Boshia et al. (2016) included an assessment of the nutritional content of wild enset individuals in comparison with domestic varieties. They analyzed *kocho* produced from three wild and three cultivated varieties after fermentation for 30 or 90 days. In general, the cultivated plants scored better than the wild ones for protein, fat, sugar, and mineral content, but the wild plants contained greater starch. It is important to note

that farmers partly identify different enset landraces based on the qualities of the *kocho*, *bullla*, and *amicho* they produce (Tsegaye, 2002).

In a dietary survey of 39 households containing 237 people, Pijls et al. (1995) showed that the average daily intake of 0.55 kg of enset products provided 68% of the total energy intake, 20% of the protein and 28% of the iron, but no detectable level of Vitamin A. The low protein content is often addressed by adding alternative protein sources to the diet. For example, kidney beans or cabbage are often eaten with enset products (Abebe, Stoecker, Hinds, & Gates, 2006). Indeed the enset farming system accommodates many food plants including legumes, vegetables, and fruits in addition to animal products and the culture of adding these in food preparations that can effectively supplement the nutritional balance of the enset food system.

Enset is reported to provide important dietary micronutrients although sample sizes are low, and results highly variable. Abebe et al. (2007) in a study of subsistence farming in households in Sidama in southern Ethiopia, found that cereals (mainly unrefined maize) contributed the major source of energy, protein, iron and zinc, whereas starchy foods prepared from enset were the primary source of calcium and an additional source of iron. Atlabachew and

TABLE 2 Nutritional analysis of enset pseudostem and corm

Analysis	Unit	Pseudostem			Corm		
		Mean (SD)	Min-Max	Samples	Mean (SD)	Min-Max	Samples
<i>Macronutrients</i>							
Dry matter	% as fed	10.2 (4.8)	5.5–20.2	17	21.5 (4.6)	14.1–29.3	18
Crude protein	% DM	4 (1)	2.5–6.2	21	3.5 (1.1)	1.8–5.9	21
Crude fiber	% DM	12.3 (8.1)	5.8–23.2	5	9.3 (6.5)	3–17.5	5
NDF	% DM	56.6 (22.2)	17.6–84.2	18	46.4 (24.4)	13.1–89.3	18
ADF	% DM	14.5 (6.3)	7.4–27.5	18	6.9 (1.8)	4.8–11.3	18
Lignin	% DM	1.5 (0.7)	0.8–2.9	7	1.3 (0.7)	0.1–2.1	7
Ether extract	% DM	0.7 (0.5)	0.4–1.7	6	0.5 (0.2)	0.3–0.8	6
Ash	% DM	8.7 (2.1)	5.6–12.5	20	4.6 (1.1)	3–7.4	20
Starch	% DM	62.2 (7.5)	50–70	5	74.6 (6.6)	68–85	5
Total sugars	% DM	1.6 (0.9)	0.5–2.5	5	1.5 (0.8)	0.6–2.2	4
Gross energy	MJ/kg DM	16.6	–	–	17.1	–	–
<i>Micronutrients</i>							
Calcium	g/kg DM	9.8 (9.6)	3–34	16	2.2 (1.7)	0.5–6.1	16
Phosphorus	g/kg DM	2.6 (2.4)	0.8–8.8	16	2.5 (2.4)	0.8–8.8	16
Potassium	g/kg DM	38.3 (10.3)	20–52	16	19.6 (7.1)	8.6–30.6	16
Sodium	g/kg DM	0.1 (0)	0–0.2	11	0.1 (0.1)	0–0.3	11
Magnesium	g/kg DM	3 (3.5)	0.6–10.5	16	2.1 (2)	0.6–6.3	16
Manganese	mg/kg DM	56 (13)	40–82	12	31 (10)	10–47	12
Zinc	mg/kg DM	14 (32)	1–116	12	130 (53)	62–226	12
Copper	mg/kg DM	4 (3)	1–12	12	5 (3)	2–12	12
Iron	mg/kg DM	158 (49)	103–227	10	86 (58)	34–237	10

Note: Raw data collated from (Fekadu & Ledin, 1997; Mohammed et al., 2013; Nurfeta, Eik, et al., 2008; Nurfeta, Tolera, et al., 2008; Nurfeta et al., 2009; Talore, 2015; Zewdie, Olsson, & Fetene, 2008). Table adapted from (Heuzé, Thiollot, Tran, Hassoun, & Lebas, 2017).

Chandravanshi (2008) found that the potassium concentration in *kocho* and *bulla* was the highest, followed by sodium, calcium, and magnesium. In general, *kocho* contained more minerals than *bulla*, but both are rich in calcium and zinc compared to other locally available starchy foodstuffs and contain comparable concentration of copper, iron and manganese. Mohammed et al. (2013) reported that the corm contains 17 of 20 amino acids and has similar or higher concentrations than potato for 12 of them.

3.5 | Enset traditional medicine

Enset is widely considered an important medicinal plant in Ethiopia, with remarkable consistency across diverse ethnic groups in its reported uses, and the phenotypic traits that characterize medicinal values. Primarily, but not always, plants used medicinally have red or reddish–purple leaf blades with midribs and pseudostems that are red to a varying degree (Alemu & Sandford, 1991; Assefa & Fitamo, 2016; Tsehaye & Kebebew, 2006).

There are two principal medicinal properties commonly attributed to enset. First, boiled corm (*amicho*) of various varieties, often consumed with milk, allegedly cures fractured or broken bones (Tsehaye & Kebebew, 2006). We hypothesize that this could be attributed to high calcium content of certain varieties speeding recovery. Second, the *amicho* of several varieties are consumed with milk and butter to facilitate placental discharge in both humans and livestock (Assefa & Fitamo, 2016; Tsehaye & Kebebew, 2006). In some cases, it may also induce abortion (Tsehaye, 2002). In addition, Pijls et al. (1995) reported the use of enset root to treat nematode worms. This is supported by a report from Hölscher and Schneider (1998), who identified a novel phenylphenalenone in enset, as well as compounds already known from other Musaceae. Phenylphenalenones may have anti-bacterial, anti-cancer, and nematocidal properties Hölscher and Schneider (1998). Tsehaye (2002) found that farmers in Sidama, Wolaita, and Hadiya used the corm or other parts of specific enset landraces to cure cirrhosis, diarrhoea or venereal diseases.

3.6 | Enset microbiome and fermentation

Traditionally, the scrapped parenchymatic tissue of the pseudostem and pulverized corm of enset are buried in an earthen pit wrapped by enset leaves and subjected to fermentation, to increase the organoleptic property and shelf life. The fermentation procedure reduces toxicity of plant raw materials, while contributing to flavor (Urga et al., 1996). Some loss of protein and dry matter is associated with the fermentation process (Besrat, Mehansho, & Bezuneh, 1979; Tsehaye, 2002), possibly due to the permeability and long duration of storage for fermentation (2–3 months) in the pit, which allows leaching of water-soluble proteins and amino acids (Tsehaye, 2002). Before fermentation, *kocho* has high moisture content, neutral pH and several microorganisms, including aerobic

and anaerobic spore formers, lactic acid bacteria, and others in the Enterobacteriaceae family and yeasts. During the initial phase, it was suggested that *Leuconostoc mesenteroides* is responsible for initiating the fermentation process succeeded by homofermentative *Lactobacillus* species. At the final stage of fermentation, the pH can drop to 3.8 accompanied by a sharp rise in acidity due to accumulation of organic acids. During the process, the number of spoiler microorganisms decreases.

Characterizing and standardizing the bacteria and yeast species currently used in enset fermentation is important for improving quality and consistency of food products and supporting the development of an effective standard set of starter cultures. Gizaw, Tsegaye, and Tilahun (2016) isolated seven non-Saccharomyces yeast species from fermented *kocho* and *bulla* samples, using metabolic and morphological character similarity to identify them as; *Cryptococcus albidus* var. *aerus*, *Guilliermondella selenospora*, *Rhodotorula acheniorum* and *Trichosporon beigeli*, *Cryptococcus terreus* (99%), *Candida zylandase* (98%) and *Kluyveromyces delphensis* (86%). However, this study only encompassed samples from a single area of South West Ethiopia, while there is substantial variation in processing techniques and potentially yeast cultures across the region (Gashe, 1987; Urga et al., 1996). More recently Birmeta, Bakeeva, and Passoth (2018) isolated cultural microbes across different stages of fermentation identifying 12 yeast and 17 bacteria species using rDNA sequencing, showing that microbial composition changes through the fermentation process.

There is significant potential to improve the efficiency and effectiveness of enset processing, which is currently a labor-intensive process. The Shakacho people, for example, add *Mandillo* (*Crassocephalum macropappum*) stem during enset fermentation, which appears to result in a pH lower than natural fermentation. As a result *Mandillo* is thought to better reduce spoilage and increase shelf life (Gonfa, 2016). Ashenafi (2008) and Tafere (2015), in general reviews of fermented products in Ethiopia, highlighted the value of controlled fermentation studies with selected cultures and starters to optimize the processes involved. Both Hunduma and Ashenafi (2011) and Gizaw et al. (2016) recommended that this could reduce labor for women, help to avoid spoilage during fermentation, improve the long-term storage and product quality, and reduce waste and increase food security.

3.7 | Cultural importance

Enset also plays an important cultural role for several Ethiopian ethnic groups who have traditionally cultivated Enset (Assefa & Fitamo, 2016; Negash & Niehof, 2004; Olango, Tesfaye, Catellani, & Pè, 2014; Shank, 1994). Tsehaye and Kebebew (2006) found that farmers in Kaffa Zone (SNNPR) are aware of, and cultivate, a number of different varieties specifically in relation to myths, poems and beliefs about their medicinal and ritual significance. Assefa and Fitamo (2016) similarly report songs and rituals associated with specific aspects of enset in the Sidama culture. The Gurage people,

Box 2 A framework for ethnobotanic surveys of enset across diverse communities and agrisystems in Ethiopia

Ethnobotanic survey framework

- Research programmes should be consistent with the International Society of Ethnobiology Code of Ethics, outlining the proposed research to candidate farmers, with similar explanations to local agricultural extension agents. International researchers should be mindful of developing appropriate Access and Benefit Sharing Agreements (ABSAs).
- Communication with other researchers, particularly those that may be working in the area or wider region is crucial to avoid duplicated work effort and survey fatigue—particularly among communities close to agricultural universities, field stations or readily accessible on major roads.
- Hypothesis generation and study design should be clearly defined and aim to minimise confounding variables. For example, analyses are frequently reported that compare farms among Ethiopian agro-ecological zones, however if differences are found it is difficult to conclude whether the driver is, for example, climatic, edaphic or socio-cultural.
- Location (GPS) should be reported in addition to local village, *kebele* and *woreda* names. Grid references can be reported at ~1 km resolution with data aggregated within study sites to protect farmer anonymity.
- The method used to select farmer respondents is important to reduce risk of bias. Many studies use model farmer or key informant interviews, which are appropriate for some questions, whilst comparatively few have used random surveys.
- Key data to ensure usability of survey data by other researchers include; location, responded selection method, landrace names, the local language, the social or cultural group and if appropriate, sample sizes and processing method.
- Additional metadata should be collected and reported to maximize the utility of data for other researchers, such as; alternative uses, medicinal applications, disease or frost tolerance, pest and pathogen incidence, identifying morphological features, co-cultivated crops, harvesting cycle, processing methods or other indigenous knowledge reported to the investigator.
- Raw data should be made readily available and accessible, for example in theses, academic paper appendices, supplementary materials or online repositories. Open data and research is critical to accelerate the food security potential of enset.

to whom enset is an important staple, label themselves the “people of enset” (Shank & Ertiro, 1996). Sahle et al. (2018) described the role of enset in Gurage economic and social life, which involves the extensive and well-planned cultivation and storage of enset alongside other crops such as coffee and khat in a mixed horticulture. Within the family, women have the major role in processing and cooking of foods from enset and it is often described as a “women crop” on account of women's significant role in the processing, cooking, and selling of enset products (MacEntee, Thompson, Forsido, & Jihad, 2013).

4 | CONCLUSIONS AND A FRAMEWORK FOR SUSTAINABLE DEVELOPMENT

Due to the complexity of enset propagation, management, harvesting, and processing, enset agricultural practice is currently inseparable from the ethnobotanical knowledge housed by numerous Ethiopian ethnic groups for which enset is a starch staple. Therefore it is unsurprising that compared to other crops, enset has not transitioned at any scale to industrial production. Only 99 tons were reported from commercial farms in the period 2011–2015, and we consider these data and the existence of commercial farms questionable (Central Statistics Agency, n.d.). A combination of complex ethnobotanic knowledge, the relative isolation of highland agroecologies and long-term cultural boundaries is likely to have impeded the spread of enset historically. Indeed from field observations by the authors, the distribution of enset agriculture appears, in many areas, to more closely match the distribution of specific cultural groups, rather than environmental conditions—although empirical evaluation of enset distribution remains to be performed. Future sustainable development of enset will depend on appropriate and equitable documentation and exploitation of this extensive knowledge. For example, in the context of increasing disease incidence in the Musaceae and the impact of climate change on East African agriculture, there are considerable opportunities in recording farmers perceptions of disease resistant, drought tolerant and early maturing landraces to guide breeding and genomic analyses (Borrell et al., 2018). There is also likely to be considerable undocumented ethnobotanic knowledge on cultivated enset that is in danger of being lost. For this reason, we outline in Box 2, a framework within which to report data from enset ethnobotanic studies, to help ensure that comprehensive quantitative information is gathered and documented to facilitate use and interpretation by other researchers. In the longer term, shifting the range of current agricultural systems such as enset-chat, enset-cereal-vegetable, and enset-tuber, or development of novel crop combinations, rather than enset-coffee, may be important for adaptation to changing climate. This, combined with genetic surveys, modern crop breeding, improved processing and selection of appropriate landraces is likely to position enset as an important climate-smart starch staple for Ethiopia and beyond.

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AUTHOR CONTRIBUTIONS

JB developed the outline, carried out a major part of the literature review and edited the manuscript. MG, GB and KJ reviewed literature and contributed key sections on topics within the manuscript. SD and PW supervised the research project. All authors helped revise and finalize the manuscript. All authors read and approved the final manuscript.

DATA AVAILABILITY STATEMENT

The data analyzed during this study are freely available from the Central Statistics Agency of Ethiopia (<http://www.csa.gov.et/survey-report/category/58-mehar-main-season-agricultural-sample-survey>). We provide our collated data in Supporting Information files Dataset S1 and Dataset S2. Scripts for plotting Figures 2 and 3 are provided at https://github.com/JamesBorrell/enset_production.

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SUPPORTING INFORMATION

Additional supporting information may be found online in the Supporting Information section.

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