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The re-emergence of Liberica coffee as a major crop plant

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The failure of Liberica coffee as a global crop plant by the turn of the twentieth century was due to a number of factors, including the inappropriate selection of material for global dissemination. Renewed interest in this species, particularly in the excelsa variant, is evident across the coffee supply chain. In a warming world, and in an era beset with supply chain disruption, Liberica coffee could re-emerge as a major crop plant.

The global supply of coffee depends on two species: Arabica (*Coffea arabica*; around 55% of global production) and robusta (*C. canephora*; around 45% of global production)[1]. In 2021 and 2022, shortfalls in global stocks of these two crop species led to a dramatic increase in the price of coffee, which in the case of Arabica resulted in a short-term doubling of commodity prices[2]. Production deficits were either associated with the compounding influence of drought (as in the case of Brazil during recent frost episodes)[2] or were as the direct result of drought in other coffee-growing countries[1], although other factors were in play, including the COVID-19 pandemic[3]. These events demonstrate the link between weather perturbations and market price, and the vulnerability of coffee to abiotic stressors. Climate change impact studies based on computer modelling imply severe declines in both yield[4] and suitable climatic conditions[5] for coffee across this century. This is set against a backdrop of increasing global demand: since 1990/1991, the total production of the major coffee-exporting countries has risen from 93,230,000 × 60 kg bags (5,593,800 metric tonnes) to 165,053,000 × 60 kg bags (9,903,180 metric tonnes) in 2019/2020[6], an increase of 77% over three decades. For these reasons, and a range of other factors, the long-term sustainability of the multi-billion US-dollar coffee sector[1] is of major concern in an era of anthropogenic climate change[7].

Climate change adaptation

There are three main climate change adaptation options for coffee farming: (1) the relocation of coffee to areas with suitable climates, (2) adapting coffee farming practices, and (3) the development of new coffee crop plants[8]. Of these options, number (3) is likely to be the least disruptive, the most cost-effective and probably the most successful[8]. The idea of broadening the coffee crop portfolio, with new cultivars, hybrids and alternative species (including underutilized crop species) is receiving renewed attention[7,8] with a focus on forgotten or underutilized species, particularly those that were once cultivated and exported at scale[8,9]. One species now receiving increased consideration and focus is Liberica or Liberian coffee (*Coffea liberica*), as witnessed by the increasing number of popular articles on the internet since around 2018, the steady increase in retail availability (especially via the internet) and the take-up by farmers in Africa and Asia.

Historical and present-day observation of Liberica coffee

In order to better understand the history of Liberica coffee, we examined museum collections including: 892 herbarium specimens from seven herbaria (with the following herbarium codes: BM, BR, K, MO, P, UPS, WAG (herbarium codes follow standard abbreviations)[10,11]); 35 commercial samples (1872–1924) from the Economic Botany Collection, Royal Botanic Gardens, Kew; and literature (see References). In situ observation of Liberica coffee cultivation was made in Cameroon, Malaysia, Sierra Leone and Uganda (2002–2022); and observation of wild populations was made in Uganda (2020–2022). In Uganda (2020–2022) we assessed value chain functionality, from farm to consumer, agronomic performance (across 200 farms) and post-harvest processing and quality (five farms).

The rise and fall of Liberica coffee

The history of Liberica coffee as a crop plant is complicated and compelling[12–16]. Indigenous across much of tropical West and Central Africa[17], Liberica was disseminated from upper West Africa, and notably from Ghana, Liberia and Sierra Leone, in the 1870s for use as a coffee crop plant[13,14,18–22], although its history in cultivation and commercialization dates back to the early 1800s[12]. It rose to prominence from the late 1870s onwards as a replacement for Arabica coffee in southern Asia (notably, in Sri Lanka[15,16]) and Southeast Asia, which at the time were succumbing to the outbreak, rapid spread and highly destructive nature of coffee leaf rust (*Hemileia vastatrix*)[12,18]. By the end of the nineteenth century, coffee leaf rust had annihilated Arabica coffee cultivation across much of southern and Southeast Asia[16]. During the latter part of the nineteenth century, between 1880–1900, Liberica sat alongside Arabica as the main coffee species of global commerce[12]. It was robust and high yielding, the fruits remained on the tree when ripe (rather than falling to the ground, and thus enabling synchronous harvesting, even though fruit ripening may not be synchronous), it had large fruits and seeds (that is, coffee beans), it had assumed or observed pest and disease resistance, and it had the ability to grow in warm, lowland (0–1000 m elevation) locations[13–15,18,21–25]. Some had assumed or observed drought tolerance[13,14], although others did not, stating that it preferred a climate with a more even spread of annual rainfall and a higher humidity[13]. Liberica has a robust growth habit (where a tree grows to 5–11 m tall)[14] and large (up to 42 cm long × 20 cm wide), thick leaves, as well as its big fruits (which are the size of walnuts (*Juglans regia*)[14] or small plums (*Prunus* sp.)[13,26] and grow up to 30 × 25 mm) and large seeds (up to 20 × 12 mm). These factors must have been instantly appealing to coffee sector stakeholders at the time, particularly those witnessing the failure of Arabica[15] (Fig. 1b). As Liberica became established, there was even the notion that it could

Fig. 1 | Liberica coffee and plant. a, Liberica coffee (*C. liberica* var. *liberica*) as introduced to Sri Lanka in the early 1870s. Note large fruit with thick fruit pulp (also known as mesocarp) and large, narrowly ellipsoid seeds. **b**, Mature plant of Liberica against Arabica (suffering from coffee leaf rust) with farm worker for scale. Adapted from ref. [15].

replace Arabica and open up the coffee growing frontier (due to its ability to grow in warm, low elevation environments[12,19,20], as opposed to the cool-tropical, high elevation conditions required for Arabica[8]). Replacement of Arabica did not materialize, but during the last two decades of the nineteenth century, the area available for coffee production was expanded to a considerable extent using Liberica, with extension across the world's low elevation tropical belt, including in South America, several of the Caribbean islands, Africa, the Indian Ocean Islands (including in Madagascar and the Seychelles), Asia (including in India, Malaysia and Java) and Australaia[12–14,19,20,24,25,27,28]. Even though the success of Liberica was not universal, for three decades it became a widespread crop plant in upper West Africa, Madagascar and Asia (for example, India, Malaysia, Philippines, Java). For some it worked, for others it did not, as recorded in communications sent to the Royal Botanic Gardens, Kew from 1882–1888[13,18–20], for example.

The rapid ascendency and global importance of Liberica coffee was short-lived, partly (or perhaps mainly) due to its uncharacteristic flavour profile[12,14,28], poor flavour[26,29] and poor quality[12,14,18], which resulted in disfavour amongst coffee merchants[13] and in weak consumer demand[12,15]. The flavour issues and low quality were largely the result of difficulties in post-harvest processing; these difficulties were due to the large size of the fruit, its thick rather tough skin (epidermis) and thick pulp (mesocarp) (shown in Fig. 1). The fruits were difficult to de-pulp and dry, and the coffee beans (i.e. seeds) were often either over- or under-dried (resulting in a suboptimal seed (%) moisture content) and often suffered if the coffee was being transported as dried fruits or as parchment (after pulping)[13,14,18]. Liberica certainly had the ability to produce good coffee, but required careful attention, as recorded in various reports of the day, for example: "No. 1, very good, bold, clean Liberian, well prepared and the best we have seen,...; No. 2,

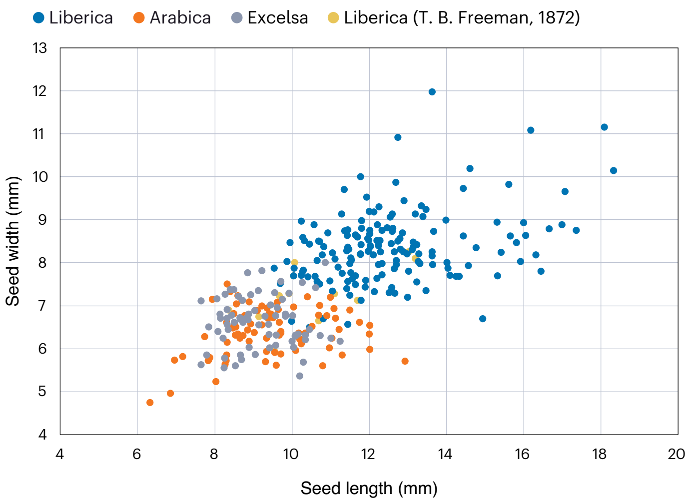

Fig. 2 | Seed length versus width for Liberica, Arabica and excelsa coffee samples. This scatter plot includes data points for: *C. liberica* var. *liberica* (Liberica), *C. arabica* (Arabica) and *C. liberica* var. *dewevrei* (excelsa) from unroasted (i.e. green coffee beans), unscreened (i.e. not size-sorted by the producer) commercial samples and one of the original introductions of Liberica (introduced by T. B. Freeman in 1872 – see main text). There are fourteen Liberica samples that were taken between 1872–1924 (origins of samples are: Ghana, Grenada, Jamaica, Java, Nigeria, Seychelles, Sierra Leone (for two samples), Sri Lanka (for two samples), St. Lucia and Uganda (for two samples)), one Liberica sample taken in 2018 (from Costa Rica) and two taken in 2022 (from Malaysia and the Philippines), making 17 samples in total. There are eight Arabica samples taken between 2001–2018 (their origins are: Brazil, Burundi, Colombia and Ethiopia (for five samples)). There are two excelsa samples taken in 2021 (from Uganda) and five taken in 2022 (from Guinea, South Sudan (two samples) and Uganda (two samples)), making seven samples in total.

in parchment, very hard and apparently over-dried; colour and quality of bean very inferior to No. 1...”[18]. The ability of Liberica to not drop its fruits when ripe, originally considered an attribute[12–14,18], may have been an additional reason for the negative flavour reviews and poor quality, perhaps in combination with post-harvest processing issues (as above). Over-ripening leads to fermentation of the fruit pulp and the development of negative sensory and quality characteristics in the coffee beans. In some markets, Liberica was unpopular because of the large size and the often-elongated shape (Fig. 1 & 2) of its coffee beans; smaller-sized beans, like Arabica, were preferred[24]. Apart from issues relating to flavour and quality, there were other factors in play that contributed to the demise of Liberica coffee. The fact that it was not fully resistant to coffee leaf rust[16,24,30–32] was a key consideration in Sri Lanka and no doubt in other countries[12], although many reported that the rust itself caused little harm to Liberica[14,19]. Perhaps more pivotal in the decline of Liberica was the discovery, swift and effective global dissemination, and rapid adoption of robusta coffee (*C. canephora*)[12,24,33], which was found to be extremely resistant to coffee leaf rust, high-yielding, robust in cultivation, easy to process, lacking in particular flavour characteristics (that is, useful for blending with Arabica, to add body etc.)[12] and able to crop in warm, low-elevation, perhumid (i.e. low precipitation seasonality) environments[7,9]. The enormous expansion of Arabica production in Brazil from the end of the nineteenth century onwards, which resulted in falling global market prices for coffee, and the uptake of rubber have been regarded as key contributory factors to the decline of Liberica in Malaysia[12,24], but market factors would have impacted all Liberica (and all other coffee)-producing countries. Despite the rapid demise of Liberica after 1900, small-scale cultivation of Liberica persisted, especially in Africa and Asia. Low-level commercial production has been maintained in some Africa countries, in Malaysia, in the Philippines and in parts of Indonesia[26], where either the flavour profile is preferred over Arabica and robusta[26,34,35] or it is easier to grow[36,37]. During the twentieth century, it was said to represent about[26] or less than 1%[38] of global production.

An unfortunate choice?

The large-fruited and large-seeded plants used for the dissemination of Liberica, from the early 1870s onwards, appear to represent early selections of cultivated stock, probably from upper West Africa (Ghana and Sierra Leone)[13,14] and, as observed by us, from commercial samples of that era. Study of literature[35,38–42], herbarium specimens and economic botany collections from 1872–1924 (held at Royal Botanic Gardens, Kew), show that this type of Liberica is uncommon in the wild. A sample (24 seeds) of one of the first introductions of Liberica to England, taken in 1872 from the plantation of T. B. Freeman in Ghana[14], shows considerable variation in seed size, with large and smaller seeds (Fig. 2). These data suggest large seeds may have been selected on the basis that ‘bigger is better’, which in hindsight represents an unfortunate miscalculation, given the difficulty in processing these large-fruited and large-seeded types. In fairness, the use of Liberica was an emergency response to the emerging coffee leaf rust crisis in Sri Lanka[12,15], for which expediency was necessary, with few opportunities for field and commercial trials and longer term observation. There may have also been unconscious selection, as many of the earliest introductions were made using seed[20] – the larger variants may have better-survived the long sea journeys required at that time[20]. Moreover, other forms of Liberica, which were later found to possess a greater number of positive agronomic attributes (see below), were unknown during the 1870s.

Excelsa coffee

Towards the end, and just after, the short-lived success of Liberica coffee, numerous allied species were described as new to science[17] to account for the substantial morphological variation in Liberica[42]. Amongst these, the names *Coffea dewevrei* and *Coffea excelsa*, described as new species in 1899 and 1903, respectively, are of particular note. During the earlier part of the twentieth century, *C. excelsa* was recognized by many as a separate species from Liberica, based on its physical appearance, and agronomic and sensory differences[14,26,35,43–45]. From the 1940s onwards, taxonomists and systematists recognized it as a botanical variety of Liberica, that is, as *C. liberica* var. *dewevrei*[17,46]. Morphological and molecular data[37,42,47–49] support the recognition of two varieties for *C. liberica*: var. *liberica* and var. *dewevrei*. The apt epithet ‘excelsa’ has persisted and is still the most widely used common name for var. *dewevrei*[17,36,37,47–49]. Excelsa is used in the remaining narrative for var. *dewevrei*, and Liberica is used to represent var. *liberica*; ‘Liberica *sensu lato*’ is used for the species.

Excelsa coffee merits special attention when considering the suitability of Liberica *sensu lato* as a crop plant, especially as it only became known to science during the commercial demise of Liberica. In terms of its agronomic and sensory attributes, it was often considered superior

Table 1 | Reported and estimated yields for *C. liberica* var. *liberica* (Liberica), *C. liberica* var. *dewevrei* (excelsa), *C. canephora* (robusta) and *C. arabica* (Arabica)

Species	Clean coffee yield (kg per ha)	Country	Tree spacings (m)	Trees per ha	Kg of clean coffee per tree	Source
Liberica	508–2,540	Malaysia	—	280	—	Anon.(a) 1890[21,28]
Liberica	1,397	Malaysia	—	—	—	Anon.(b) 1890[21]
Liberica	1,690–2,620	Malaysia	3 × 3	1280	—	Muhamad Ghawas (2006)[32]
Excelsa	350–1,100	Java	—	—	—	Cramer (1957)[27]
Robusta	1,050	Java	—	—	—	Cramer (1957)[27]
Robusta	600–1,200	Uganda	3 × 3	1111	—	UCDA[a] (2022)
Arabica	500–1,600	Uganda	2.5 × 2.5	1600	—	UCDA[a] (2022)
Excelsa	877	Uganda	7 × 7	204	4.3	Estimated (2021/22)
Excelsa	1,720	Uganda	5 × 5	400	4.3	Estimated (2021/22)
Excelsa	1,754	Uganda	7 × 7	204	8.6	Estimated (2021/22)
Excelsa	3,440	Uganda	5 × 5	400	8.6	Estimated (2021/22)

Estimated yields for excelsa are based on kg of clean coffee per tree × number of trees per hectare (ha). [a]Robusta and Arabica yields are for comparative purposes only; global yield variance for clean coffee production in these species is substantial (for example, 200 kg per ha to >3,000 kg per ha; see also https://fdc.nal.usda.gov/https://fdc.nal.usda.gov/ and http://www.fao.org/faostat/en/#home) depending on location, climate, agronomy (e.g. planting density, soil improvement and shade cover) and inputs (e.g. fertilizer, soil improvements, irrigation etc.).

to Liberica. It was noted for high yields[26,31,43], which in some countries were comparable to, or exceeded, robusta[31] and Arabica[39] (Table 1). Other positive agronomic attributes included synchronous fruit ripening, tightly clustering fruits at the leaf nodes (like robusta, but unlike many variants of Liberica) and the ability to withstand pruning[31,43]. The Arabica-sized fruits, which have a thinner, softer pulp (roughly 2 mm thick) compared to the large-fruited Liberica (3–6 mm thick; Fig. 1) and contain Arabica-sized seeds (Fig. 2 & 3), were seen by many as a major advantage over Liberica[26,31,35,43]. The fruit of excelsa can be easily pulped, without the need for additional or modified equipment, or more labour-intensive activities, compared to Liberica, with its large fruit, thick skin and tough, thick pulp[14,50]. For processing methods that do not involve pulping (i.e. those that produce sun-dried coffee), the softer, thinner pulp and smaller, Arabica-sized seeds make drying the fruit easier and decreases the risk of fermentation, which would otherwise diminish quality and negatively influence flavour. Significantly, a thinner pulp improves the conversion ratio (often referred to as outturn) of fresh fruit to clean coffee (see below). Excelsa has partial resistance to coffee leaf rust and therefore the potential for selection of improved coffee leaf rust resistance genotypes[31], nematode resistance[51] and perhaps partial resistance to coffee berry borer (*Hypothenemus hampei*)[26]. Farmer and producer feedback from Uganda and South Sudan (2018–2022) report either insignificant or zero susceptibility to coffee berry disease (*Colletotrichum kahawae*) for excelsa. Coffee wilt disease (*Gibberella xylarioides*) was first reported on excelsa coffee in the Central African Republic in 1927[51] and later caused widespread damage to Liberica and robusta coffee across large areas of tropical Africa. It is still a major constraint for robusta production today, but has not been reported during our field surveys of excelsa in Uganda or in South Sudan. Continued vigilance and dedicated research are required to better understand the level of resistance of excelsa (and Liberica) to coffee leaf rust, coffee berry disease and coffee wilt disease. Based on the wild origins of excelsa (which include lowland northern Central African Republic, southern South Sudan and western Uganda) and the experiences of excelsa in cultivation, drought tolerance (and the notion that excelsa is more drought tolerant than robusta[29,31]) has been either assumed or experienced[14,24,26,29,30,43,52]. Others have noted[31] or demonstrated[53] that excelsa has tolerance to low temperatures and even to frost[39]. In terms of flavour quality, excelsa has been reported as: "mild and far from the extreme bitterness of Liberica"[26], "with mild flavour, of fair quality in some strains"[26], resembling Arabica coffee from Harar (in Ethiopia)[39], producing "an agreeably flavoured beverage"[14] or simply as a "good coffee"[24]. During the first half of the twentieth century, many saw great potential in excelsa[14,28,30,31,39] or at the very least recognized its usefulness[24]. It should be carefully noted that most of the plants being grown today (and the coffee being produced) as excelsa (or as *C. liberica* var. *dewevrei*) are variants of Liberica (var. *liberica*) with smaller seeds than the traditional type.

Recent uptake of excelsa farming in Africa

Despite the apparent potential of excelsa, the use of this coffee became neither commonplace nor locally abundant, probably because Arabica and robusta served the coffee sector well enough. However, renewed interest in excelsa coffee is now clearly evident. In Uganda, at least 200 farms are now growing excelsa, and this number is growing year-on-year, mainly due to farmers shifting from farming robusta to farming mixed robusta–excelsa or farming excelsa only. South Sudan has recently seen the planting of a large excelsa-only estate and the initiation of an extensive outgrowers programme, which is currently at 200 ha from several hundred smallholdings (E. Stiles, Equatoria Teak Company, personal communications). This uptake is notable in itself, but there are two other key points: first, the preference to plant excelsa (over robusta) has been farmer-led in both countries, rather than being based on advice from external stakeholders or intervention agents; and second, excelsa is an indigenous plant of Uganda and South Sudan, where it occurs naturally in low elevation forests bordering the Democratic Republic of Congo (although its range includes other African countries[17]). In both cases, based on the considerable morphological variation observed on farms, the planting material has

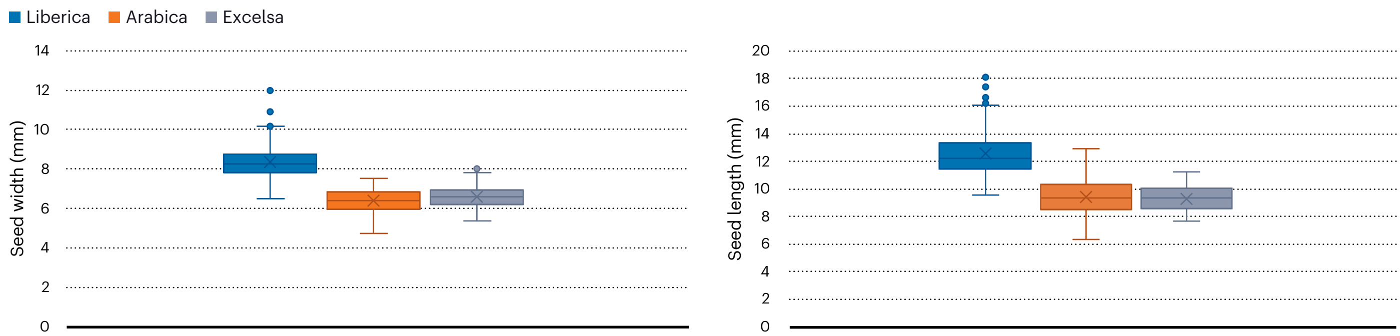

Fig. 3 | Seed length (left) and width (right) for *C. liberica* var. *liberica* (Liberica), *C. arabica* (Arabica) and *C. liberica* var. *dewevrei* (excelsa) from unroasted (green coffee beans), unscreened (i.e. not size sorted by the producer) commercial samples. Seed length (mm) quartile values (Q0 (minimum)/Q1/Q2 (median)/Q3/Q4 (maximum)): Liberica (6.50/7.80/8.29/8.75/11.98), Arabica (4.75/5.98/6.42/6.81/7.51) and excelsa (5.36/6.23/6.59/6.92/8.01). Seed width (mm) quartile values (Q0 (minimum)/Q1/Q2 (median)/Q3/Q4 (maximum): Liberica (9.54/11.45/12.25/13.31/18.33), Arabica (6.32/8.53/9.36/10.28/12.93) and excelsa (7.65/8.60/9.35/10.03/11.25). See Fig. 2 for sampling details (excluding the T. B. Freeman specimen).

undergone little or no selection and resembles the diversity and range of morphological variation seen in wild populations, as observed by us in Uganda and South Sudan. According to farmers growing excelsa in lowland Uganda, this coffee (referred to by farmers using local names, or more recently as 'Liberica') has been a minor element of their farms for many decades, perhaps generations, and originally came from the forest. Upscaling of excelsa over the last twenty years in Uganda, and particularly over the last ten years or so, appears to be the result of production issues with robusta, and particularly the increasing occurrence and severity of disease (especially coffee wilt disease), drought and pests (particularly stem and twig borers). The farmers also reported (between 2016–2022) consistently high yields of 30–60 kg (and sometimes up to 70–80 kg) of fresh fruit per average-sized tree and up to 300 kg yields for very large old trees under rainfed conditions and with minimal inputs (for example, a minimal rate of fertilizer use). A fresh-fruit yield of 30–60 kg translates to 4.3–8.6 kg of clean coffee per tree, given a conservative fresh fruit to clean coffee conversion (outturn) of 7:1 (see below for discussion on conversion ratios). Even given the larger spacing required for Liberica-type coffees, which ranges from 5–7 × 5–7 m (observed) to 3.9–4.5 × 4.5–5.4 m (reported)[26], the yields per hectare for excelsa are respectable to substantial (Table 1). Maturity of yield capacity comes in the fifth or sixth year after planting, which in most cases is one or two years after Arabica and robusta. In Uganda, average robusta yields (grown in the lowlands, like excelsa) are between 0.5–1.1 kg per tree, and for Arabica (grown in the highlands) yields are between 0.3–1 kg per tree (Table 1). Robusta usually produces a smaller additional (fly-crop) between April–August after the main crop (which occurs between October–February). Excelsa coffee flowers from March–April and crops 11–12 months later[26]; robusta takes around 11 months between flowering and producing the main crop[52] and Arabica takes around nine months[54]. In 1915 and 1916, low yields were reported for excelsa in Uganda, but this was based on genotypes imported from Java[14,29], which may have been unsuitable for conditions in Uganda. Indeed, they were probably not excelsa at all, as this species was only known to science in 1903[55], and commercial samples (which can be found in Kew's Economic Botany Collection, No. 53456, dated 1924) from Uganda that are labelled as excelsa, are in fact large-seeded Liberica. In Uganda and South Sudan, post-harvest processing (including drying) and pre-shipment processing (including hulling or milling, grading and sorting) of excelsa are similar to processing carried out on Arabica and robusta, and is undertaken using equivalent protocols and machinery. In Uganda, excelsa is usually combined with (or sold as) robusta for export, partly due to confusion over the identity of excelsa (which is sometimes considered a large, thick-leaved type of robusta; and both can have similar sized coffee beans) and partly due to convenience. This year (2022) will see what is probably the first dedicated export of excelsa coffee to the United Kingdom (Clifton Coffee Roasters, personal communications). Limited exports of excelsa from Uganda to Italy have been made over the last few years under the name kisansa coffee, without reference to Liberica or excelsa.

Excelsa cup profile

Contemporary flavour assessments, of satisfactorily processed excelsa coffee from Uganda and South Sudan, that have been executed using standard methodologies (for example, the SCA cupping protocol and Arabica roasting profiles (e.g., those available for the IKAWA Pro50)) reveal a mild, smooth, pleasant-flavoured coffee of low to medium acidity and low bitterness, as per historical accounts (see above). Tasting notes include cocoa nibs, peanut butter, dried fruits, Demerara sugar and maple syrup; and for samples from South Sudan, there are notes of raspberry coulis, figs, plums and milk chocolate. The difference in flavour profile between Liberica, Arabica and robusta, and the differences between Liberica and excelsa, substantially broaden the flavour experience for coffee as a beverage, which can be viewed as either positive or negative. Overall, excelsa has a cup profile much closer to Arabica, compared to excelsa versus robusta.

Reworking traditional Liberica

Renewed interest in traditional, large-seeded Liberica (*C. liberica* var. *liberica*) is evident. Producers in Asia (including in India, Malaysia, Indonesia and the Phillippines) and Africa (for example, Sierra Leone) are responding to consumer interest (and demand) in this coffee. Renewed interest from farmers is perhaps also due to the low farm-gate prices paid for robusta coffee, which has a commodity price at least two fold lower than Arabica[2]. Work on the post-harvest processing (i.e. pulping, washing, fermenting and drying) of Liberica has led to substantial improvements in its quality and flavour, as evident in numerous articles online. This is consistent with historical reports, which show that optimized post-harvest processing can have a substantial influence on quality, as reported above. Contemporary assessments for Liberica indicate high levels of natural sweetness (a positive attribute for coffee quality), a rich, bold mouthfeel, low acidity and flavour notes of chocolate, jackfruit and other tropical and non-tropical fruits. To meet consumer interest and demand, Liberica from Malaysia and the Philippines has started to be sold much more widely in Europe, the USA and Asia. Liberica can be high yielding (Table 1), particularly in Malaysia, where Liberica dominates coffee production (Liberica 73%; robusta 27%[50]) and reaches production maturity 5–7 years after planting[36]. One of the major disadvantages of Liberica, particularly for the larger fruited and seeded types (Figs. 1–3), is the low conversion of fresh fruit to clean coffee, due to the higher ratio of pulp to seed mass compared to other coffees. Reported conversion ratios for Liberica are 8.3:1–12.5:1[26,30,36]; thus, 8.3–12.5 kg of fresh fruit is required to produce 1 kg of clean coffee. This is unfavourable compared to the conversion ratios for Arabica, which has conversion of 5–6.25:1[54], and excelsa, for which the conversion is 6:1–6.8:1[26,30], although ratios for speciality (i.e. high quality) Arabica can be around 8:1 or higher[56]. Low conversion rates add considerable costs – since more fruits are required to produce equivalent amounts of clean coffee[18], there are increased labour requirements for harvesting and processing, and additional post-harvest and pre-processing transport expenditures.

Caffeine content

Wider acceptance of Liberica (var. *liberica*) and approval of excelsa (var. *dewevrei*) by retailers and coffee consumers based on flavour is likely to be a contributory, but not dominant, factor (see notes on supply chain disruption, below) in the return of this species as a major crop plant. As well as flavour, caffeine content is a key consideration for retailers and consumers. The caffeine content of Liberica coffee is broadly favourable for widespread commercialization, with a mean caffeine content of 1.2% dry matter basis (dmb) for var. *liberica* (Liberica) and 0.94% dmb for var. *dewevrei* (excelsa)[57], which is similar to Arabica (1.2% dmb)[58] but much lower than robusta (2.6% dmb)[57]. Despite its global importance, robusta coffee is seldom used to produce 100% whole-bean coffee in the major coffee markets due to its high caffeine content and (near-universal) harsh or overly bold and undesirable flavour notes[33] (for example, woody, rubbery and tobacco-like). Robusta is mainly used for instant (dried) coffee and for blending (10–40%) with Arabica to make espresso coffee or espresso-based coffees. Like Arabica, Liberica coffees are therefore suitable for 100% whole-bean coffee, which is a key attribute for commercialization in many sectors of the coffee retail market.

Underutilized coffee species and their uptake in a changing world

Unlike other promising alternative coffee crop species, such as stenophylla coffee (*Coffea stenophylla*)[8], Liberica is widespread in cultivation across the coffee growing belt, albeit mostly at low density, mainly as a legacy of the dissemination efforts at the end of the nineteenth centrury[12–14] and by virtue of it being a robust and long-lived plant. The extent of cultivated excelsa is yet to be ascertained, particularly as many plants labelled as excelsa represent the smaller-fruited and smaller-seeded types of Liberica, or perhaps hybrids between Liberica and excelsa.

To fully re-invigorate Liberica to the level of a major crop plant will require input from a range of stakeholders. The flavour profile and agronomic characteristics (yield, fruit and seed size, phenology, and resistance to major pests and diseases) vary across the species, as outlined above, and within each of the two botanical varieties. Careful selection of the best-performing genotypes and the generation of selected lines would be an essential part of any dedicated, major upscaling. Multi-location field trials, disaggregated by present and projected future coffee growing climates, other abiotic parameters and pest and disease assessments would be a key requirement for understanding the medium- to long-term climate resiliency and benefits as well as downsides of Liberica and excelsa coffee.

In a changing climate, Liberica offers (at the very least) the potential to grow commercially viable, and perhaps high-value, coffee under much warmer conditions (and at lower elevations) than Arabica[8] and may offer improved climate resiliency over robusta[29,31]. Despite higher flavour quality in other underutilized species, particularly stenophylla[8] and eugenioides[7] (*Coffea eugenioides*), Liberica and excelsa offer almost ready-made crop options. The bean size of stenophylla is similar to Arabica, but its productivity is lower[8] and would require some development for commodity-level use; eugenioides has a small bean size and very low productivity (for example, 200 g of clean coffee per tree), and will remain a niche crop unless substantial development is undertaken. We have already observed that coffee farmers, and other value chain actors, are perceiving Liberica as a means of improving the price of coffee, over robusta, at lower elevations. Modelled mean annual temperatures and annual rainfall are: 18.7 °C per 1,614 mm for Arabica; 23.7 °C per 1,601 mm for robusta and 23.9 °C per 1,699 mm for Liberica[8].

Ultimately, the scale of uptake for Liberica (including excelsa) will depend on the scale of demand, which will include demand from consumers but also from the coffee sector as a whole. The history of coffee farming demonstrates that underutilized species are only likely to come into major usage as a response to drastic disruptions in the supply chain. In the case of coffee, the introduction and scaling of Liberica, and then robusta, was the response to the major devastation caused by the coffee leaf rust epidemic towards the end of the nineteenth century. The level and intensity of climate-related issues, perhaps in conjunction with pest and disease problems[16], as agents of supply chain disruption for Arabica and robusta are likely to be key governing factors in the re-emergence of Liberica (including excelsa) as a major crop plant species. Regardless, given the profound influence that climate change is likely to have on coffee production nationally[5] and globally[4], we will need to be proactive in the development and establishment of alternative coffee crop species[7,8], which are able to exist under markedly altered climatic conditions. Liberica and excelsa coffee may provide part of the diversification required to achieve this objective.

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