Research Article

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Potential beverage quality of three wild coffee species (*Coffea brevipes*, *C. congensis* and *C. stenophylla*) and consideration of their agronomic use

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Abstract

BACKGROUND: Of the 130 known coffee (*Coffea*) species, very few have been properly evaluated for their beverage quality. The diversity of wild coffee species is considered critical to the long-term sustainability of the coffee sector, particularly under climate change. The challenge is finding coffee crops that satisfy agronomic criteria, now and under the altered climatic conditions of the future, as well as consumer requirements for flavour. We evaluated the sensory characteristics of three wild coffee species with four independent sensory panels, and the key environmental/agronomic requirements of these wild species based on a literature review.

RESULTS: *Coffea congensis* and *C. stenophylla* have a lower unroasted seed weight compared to *C. arabica* and *C. canephora*, while *C. brevipes* has the largest. Sensory analysis showed that the main differences between species was for the fruitiness attribute. *Coffea stenophylla* was the fruitiest wild species, and was considered an Arabica-like coffee. The flavour profile range of *C. stenophylla* covers herb-like, vegetal, floral and fruit; *C. brevipes* resembles *C. stenophylla* in some respects. Opinions concerning *C. congensis* were contradictory and several judges considered the industry-standard coffee flavour wheel not suitable for the beverage produced from this species.

CONCLUSION: The three wild species have the required sensory qualities for commercialization. According to published data, *C. stenophylla* has agronomic potential, especially in warmer climates than Arabica areas. *Coffea brevipes* and *C. congensis* have the potential to be easily crossed with *C. canephora* to form interspecific hybrids capable of adapting to different climatic and agronomic conditions.

Supporting information may be found in the online version of this article.

Keywords: coffee; wild species; sensory test; global warming; specialty market

INTRODUCTION

The world market for coffee has been estimated at USD 200 billion per year, with the export market representing 75% of this value (https://www.ico.org). Global production is based on three species: Arabica (*Coffea arabica*), Robusta (*C. canephora*) and Liberica (*C. liberica*), which comprise ~60%, ~40% and <1% of the market, respectively (https://www.ico.org). There are two main elements in the commercial sector: commodity and specialty; the former dominating the market and the latter comprising ~10%, although this figure is difficult to quantify.[1] 'Specialty' refers specifically to coffee of high quality, as determined by strict criteria for physical quality and flavour (sensory characteristics) (https://sca.coffee/research/protocols-best-practices). Specialty coffees are usually linked to unique flavour profiles, due to a

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combination of genetics (the cultivar or origin), climate, and features of harvest and post-harvest processing. The criteria used today to judge the sensory quality of coffee has changed dramatically, even over recent decades. Judges are now trained to detect subtle flavour notes, classify coffees into specific categories (e.g., https://allianceforcoffeeexcellence.org/), and provide fine-level quality and hedonic assessments.

The dynamism of the specialty market requires new products, new cultivars (often referred to as 'varieties' or 'varietals') and developments in processing methods,[2] as consumer preferences evolve. A more recent developments is the use of alternative coffee species, i.e. those other than Arabica and Robusta, for providing new sensory experiences.[3] Of the 130 known coffee (*Coffea*) species,[4] very few have been properly evaluated for their beverage quality.[3] In addition to the requirements of the specialty sector, the diversity of wild coffee species is considered critical to the long-term sustainability of the coffee sector as a whole, particularly under climate change.[3,5] The challenge is finding coffee crops that satisfy agronomic and survivability criteria, now and under projected, altered climatic conditions[6,7] as well as consumer requirements for flavour.

Other than Arabica, Robusta and Liberica, there are other coffee species being cultivated on a very small scale, including *C. congensis* (Congo coffee), *C. eugenioides*, *C. racemosa* and *C. zanguebariae* (Zanzibar or Ibo coffee).[8]

Coffea eugenioides, otherwise known as Nandi coffee (mostly in Kenya), is native to several countries of the Great Rift Valley area of East Africa[9] (https://apps.kew.org/wcsp/). It has excellent sensory qualities[5] and is sold as a high-value niche coffee within the specialty coffee market; it is noted for its outstanding sweetness, low acidity (preferred by some drinkers) and fruit-driven cup profile (https://medium.com/@szhu_coffee/this-is-not-coffee-3efec0d355ea; and links therein), and low caffeine content.[10,11] At the present time its cultivation is limited to small areas in Kenya and Colombia, although high prices are required for profitability due to its very small coffee beans and extremely low productivity.

Coffea racemosa is a species native to Mozambique, Zimbabwe and South Africa.[8,9] Hallé and Faria,[12] cited by Guerreiro Filho,[13] observed the existence of small-scale cultivation of *C. racemosa* in Mozambique for local consumption. It is now being cultivated at small scale in South Africa (https://www.racemosa.coffee/). The species produces small seeds in low numbers per plant, which does not encourage wider cultivation.[8,12] Chevalier[14] indicated that the drink obtained from *C. racemosa* would be equivalent to Arabica, although Guerreiro Filho[13] cites an oral communication with Alcides Carvhalho, who states that the quality of *C. racemosa* is inferior to that of Arabica. Recent cupping reports show that this species has a very specific and unusual flavour profile.[8] *Coffea zanguebariae* is indigenous to southern Tanzania, northern Zimbabwe and northern Mozambique.[8] It is currently grown at small scale on the northern mainland of Mozambique and on Ibo and Quirimbas Islands, as Ibo coffee.[8] It was reported to grow (as Zanzibar coffee) on Zanzibar Island in the 18th and 19th centuries, but its cultivation there today has not been confirmed.[8] Its cup profile is similar to *C. racemosa* but has a larger bean (seed size) and higher yield.[8]

In order to conserve at least part of the genetic diversity of wild coffee species, *ex situ* coffee collections are located in several countries.[15] The *Coffea* Biological Resources Center (BRC *Coffea*), maintained on Reunion Island, is the result of numerous prospecting and campaigns in Africa (Cameroon, Ivory Coast, Ethiopia, Guinea, Kenya, Central African Republic (CAR), Republic of Congo, Tanzania), with the participation or support of national agronomy research centres and international institutions over a period from the 1960s to the 1980s. To date, the BRC *Coffea* collection houses 35 *Coffea* species[16] (http://florilege.arcad-project.org/fr/crb/coffea). Thanks to the availability of genetic resources at BRC *Coffea*, which includes species sourced in Cameroon, we were able to conduct the study reported here.

Other considerations aside (see above), before committing to long and expensive programs to valorize new coffee crop species, it is essential for breeders and agronomists to know their sensorial qualities, validated by academic and private sector stakeholders, preferably with the addition of statistical tests.

The aims of this study were to: (i) provide the first sensory evaluation for *C. brevipes*, alongside two imperfectly known minor coffee crops species, *C. congensis* and *C. stenophylla* (Fig. 1); and (ii) evaluate the physical characteristics of the seeds (i.e. unroasted coffee beans) of the three species. Basic agronomy information is also provided. For the purposes or this study, we employed a literature review, detailed sensory analysis and measurement of key seed characteristics. The sensory analysis was undertaken using an expert panel of 17 judges, from different coffee sector backgrounds.

MATERIALS AND METHODS

Literature review

A literature review, based on articles published in German, Dutch, English and French from the 19th century to the present day, was conducted. We attempted to capture the essence of these articles in our literature review.

Sample origin

The samples used for the measurement of the three wild species (*C. brevipes*, *C. congensis* and *C. stenophylla*) were collected in October 2020 in the *Coffea* Biological Resources Center (BRC *Coffea*), located on Reunion Island (Indian Ocean). The *C. brevipes* genotypes that are conserved in the Reunion Island collection, and used in this study, came from Western Cameroon, near Mount Cameroon.[17] The *C. stenophylla* genotypes were from Ivory Coast, and the *C. congensis* genotypes were from Central African Republic and Democratic Republic of Congo.

In the BRC *Coffea* collection, the trees used for this study grow on volcanic soil in a cooler tropical climate than the climate of their respective areas of origin, but it is a tropical climate well suited to growing coffee. The coffee trees were shade grown, under *Grevillea* sp., at 380 m above sea level. The field site has an mean annual air temperature range of 22.4–23 °C, and an annual precipitation range of 1180–1625 mm. The site is supplemented with drip irrigation.

To obtain an indication of sensory potential, the samples of the three species studied were made up of several genotypes: the aggregated *C. stenophylla* sample comprised ten genotypes, the *C. brevipes* sample 18 genotypes and *C. congensis* nine genotypes.

A further sample of *C. brevipes*, evaluated using a separate sensory protocol (see 'Sensory Analysis (cupping)', below), was obtained directly from a village production site in western Cameroon close to its wild source. This sample does not feature in the main analysis.

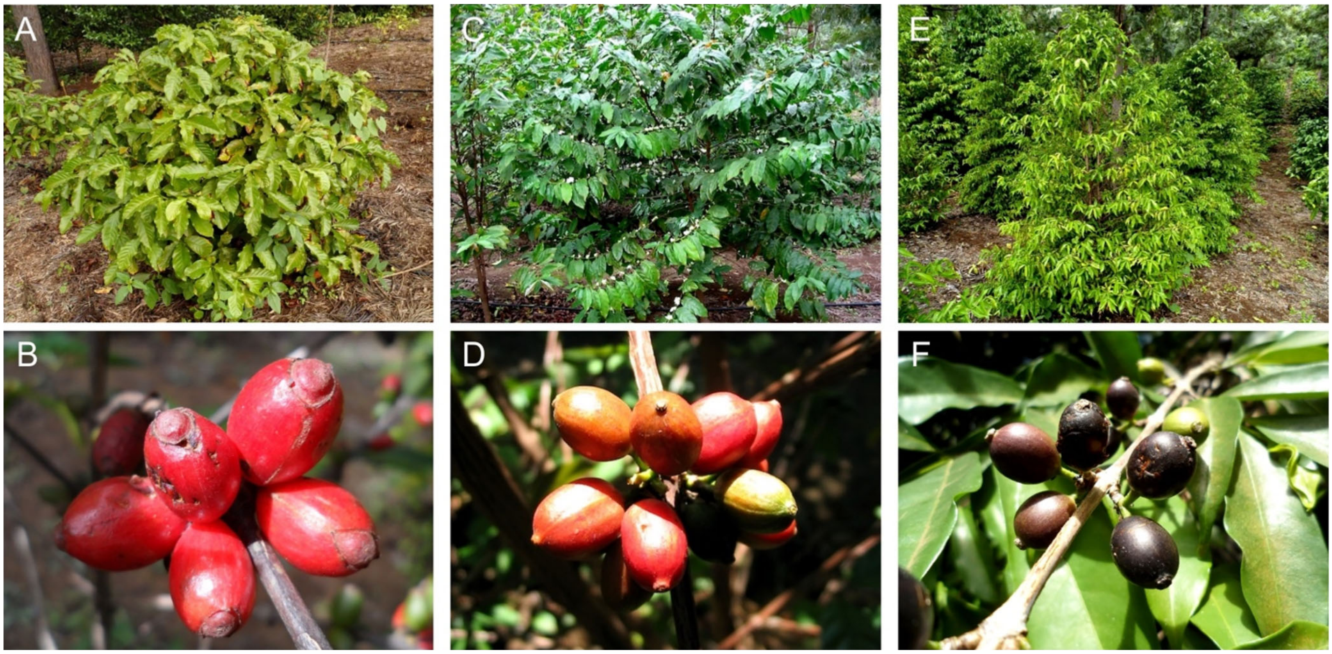

Figure 1. Habit (basic tree morphology) and fruits of three wild coffee species, *C. brevipes*, *C. congensis* and *C. stenophylla*, in cultivation at the *Coffea* Biological Resources Centre (BRC *Coffea*) on Reunion Island. From left to right: *C. brevipes* (A,B), *C. congensis* (C,D) and *C. stenophylla* (E,F). Individual pictures were extracted from the Wild *Coffea* species database[16] (Picture ©E Couturon IRD, under Licence Creative Commons, https://doi.org/10.23708/JZA8I2).

Processing of samples

The samples for each of the three wild species (Supplemental S1) underwent the same post-harvest protocol. Just-ripe coffee fruits ('cherries' or 'cherry') were harvested in the morning (3–4 kg of coffee cherry per species), transported to the processing factory, and directly processed in the afternoon by the wet processing method (depulping, fermentation and drying) to obtain approximately 500 g of green coffee beans (at 11% moisture). The fermentation process was divided into three successive steps: 'dry' fermentation with only mucilage (24 h), maceration by adding water to cover the seeds (15 h) and, finally, washing by changing the water three times during this step (11 h). Any apparently defective beans were discarded to obtain the final batch of green coffee for sensory analysis.

Two species were used as controls – two samples of *C. arabica* (Arabica) and one of *C. canephora* (Robusta)– obtained from a commercial source (Cafés Bibal, a French coffee company) (Supplemental S1). Each had undergone harvest and post-harvest processes specific to each origin (see below). They were named for this study using the species epithet followed by the first geographical place of origin: (i) Arabica 'Ethiopia' (Green coffee called by the supplier 'Ethiopia Moka Sidamo G2'; €3.52 per kg; wet process); (ii) Arabica 'Brazil' (green coffee called by the supplier 'Santos Sul de Minas'; €2.52 per kg; dry process); and (iii) Robusta 'Indonesia' (green coffee called by the supplier 'Robusta Indonesia Flores natural'; €2.72 per kg; dry process). Arabica 'Ethiopia' is a high-quality, specialty coffee. Arabica 'Brazil' was bought as a commodity-level (https://ico.org/) Arabica, and was processed naturally (sun dried) by the producers; i.e., the harvested cherry was directly spread out upon patio pavements and dried in the sun until the moisture content was around 11–12%. This coffee had a high proportion (more than 20%) of 'Quakers', which are unripe beans caused either by too early harvesting or suboptimal agronomic conditions (drought, nutrition, etc.). This defect is mainly visible after roasting. These defective beans were removed for the purposes of the sensory evaluation and density measurements. Robusta 'Indonesia' was considered to be a good-quality Robusta, with a differential premium of 20% over the standard Robusta price (https://ico.org/).

Seed weight and morphology

For each sample, we evaluated the physical characteristics of the seeds (unroasted coffee beans at 11% of water content). We measured the mass of 100 healthy green beans (W100). The area (in cm^2) and circularity (a value of 1 equals a perfect circle) of the green beans were measured by image analysis (software ImageJ/Fiji).

Sensory analysis (cupping)

The samples were evaluated using a protocol developed by CIRAD, derived from the European standards ISO 6668 and 13299 (hereafter referred to as the CIRAD sensory protocol), by the CIRAD Sensory Analysis Laboratory (Montpellier, France) in December 2020. For our application of ISO 6668:2008, three roasts were used (light, medium and dark), for each of the six samples assessed by this protocol. All samples were roasted simultaneously, for standardization, and left for a minimum of 12 h before either cupping or vacuum packing (e.g., for the sending of samples for external evaluation), to allow for degassing (mostly CO_2). The samples were ground to a medium/fine powder immediately prior to cupping. For each sample, 50 g of ground coffee was added to 1 L of boiled water (~95 °C). A Bodum French press coffee maker (i.e., an immersion brewing method) was used to prepare the beverage. The hot water was poured directly onto the measured ground coffee, making sure to wet the grounds thoroughly. Shortly afterwards, once the coffee solids had risen to the surface of the French press, the mixture was stirred to homogenize the coffee solution and solids. The mixture was left

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to stand for exactly 5 min, after which time 60 mL was poured into each cup. Sensory analysis was undertaken between 50 and 55 °C. Each sample was assessed blind; i.e., the species and origin of the sample were unknown to members of the sensory panel. Evaluation was conducted by aspirating the coffee into the mouth, directly from the sampling cup, to take the vapour and liquid to the tongue and upper palate. Each judge had their own set of samples. Four independent sensory panels (Nespresso (Switzerland), Supremo (Belgium), Jacobs Douwe Egberts (Netherlands) and CIRAD (France)) were engaged in the evaluation, comprising eight companies/organization, and 17 judges (Supplemental S2).

The following 16 variables were scored (each out of 10 points) by the judges across four categories: Odour (olfactory intensity); Taste (acidity, bitterness); Impression (astringency, body, sourness); Aroma (fruity, harsh, green, earthy, metallic, phenol, rotten, burnt, smelly) and Overall Quality (Supplemental S3).

The panel members were also asked to provide open comments on flavour attributes referring to the CIRAD Coffee Flavour Wheel. For each sample, the comments were classified on ten categories: (floral, fruit, sweet and sugary, cocoa, nuts, grain and cereal, roasted, savoury, spicy, vegetal herb-like and earthy). Categories which had more than 20% of comments were considered representative of the sample and were selected to create a schematic figure representing the main flavour attributes of the species (Supplemental S3).

Four additional yes/no questions were asked: (i) Is this Arabica coffee? (ii) Is this Robusta coffee? (iii) Could this coffee be commercialized? (iv) Is this coffee new? Yes/no responses (0/1) for the four questions were totalled by sample (3 roasts and 17 judges i.e., 51 answers) to provide a percentage score (Supplemental S3).

For statistical processing of the sensory attributes, we compared the samples by analysis of variance (ANOVA) with values of $P < 0.05$ to indicate significance. An ascending hierarchical classification (AHC; square Euclidean distance, Ward grouping method) was used to cluster the samples. The calculations were performed using the statistical software program package XLSTAT 2019.

A single sample of *C. brevipes*, sourced locally in Cameroon, was evaluated using the Specialty Coffee Association (SCA) protocol and scoring system (https://sca.coffee/research/protocols-best-practices) and sensory terminology of the SCA Coffee Taster's Flavor Wheel.[18] The sample was assessed by a panel of three judges, with a Q-Grader leading the panel and providing a brief, narrative assessment. Further details of the methods used can be found in Davis *et al*.[5]

RESULTS

Literature review

The wild coffee species *C. brevipes*, *C. congensis* and *C. stenophylla*, which we studied in the present paper, are presented in Fig. 1 for illustrative purpose.

Coffea congensis

Coffea congensis was named by A Froehner in 1897 based on a sample collected by Emile Laurent in 1896 from the Congo river islands around Mbandaka.[19,20] This species is found wild throughout the Congo Basin and adjoining areas of Western Central Africa, in Cameroon, Central African Republic (CAR), Congo, Democratic Republic of Congo (DRC) and Gabon[9] (http://apps.kew.org/wcsp/). According to Chevalier[14] and Lebrun[21] this species is very common along a large length of the Oubangui River in DRC and CAR.

Coffea congensis is confined to riverine habitats, as a rheophyte, or a species of gallery and flooded forests.[9] It is adapted to withstand periods of flooding; flowering occurs during periods of low water and fruit are borne during periods of high water.[22] *Coffea congensis* appears to prefer sandy soils, and in its natural habitats is deep rooting. It favours areas of open undergrowth and clearings. A survey undertaken in 1975[20] noted that *C. congensis* was strictly limited to riverbanks where the rivers are wide enough to create an opening in the forest, and to depressions on river islands and periodically flooded banks. These habitats have very special micro-relief mounds, 40–80 cm high, which can be almost specifically populated by *C. congensis*, delimiting a drainage network almost devoid of any other vegetation.[20] *Coffea congensis* has been named 'the coffee tree of the river' or 'of the islands',[20] because of its association with riverine habitats. Other fieldworkers report similar observations for this species in the Congo Basin (D Harris, pers. comm.).

According to some authors, *C. congensis* physically resembles Arabica,[23,24] due to the size, shape and general features of the leaves and fruits. Stoffelen and co-workers[25,26] considered it 'hardly distinguishable' from Arabica and inferred a close relationship based on morphology, although molecular phylogenetic studies reveal a close relationship with *C. canephora* and *C. brevipes*.[27-29] *Coffea congensis* exhibits considerable morphological diversity,[23] and some of the more extreme variants have been accorded taxonomic status, although these names are currently not used.[9] According to Burkill,[30] *C. congensis* is used as wild-sourced, local coffee beverage species in West Africa. Soon after its scientific discovery *C. congensis* was considered to have potential as a coffee crop species, and was disseminated widely[23] to Java and Madagascar from seeds received from MC Challot sown by Chevalier in the botanic garden of Libreville in 1900 in Gabon.[20] The current status of *C. congensis* in cultivation is poorly known, although it is reported to be growing in several coffee research collections in West and Central Africa.[15] It is probably also present in germplasm collections in India, South East Asia, Brazil and Costa Rica, and is being farmed on a small scale in India as a niche market coffee.

In the research collection in Ivory Coast, *C. congensis* needs to be grafted onto *C. canephora* to survive in ferrallitic soils.[17] Indeed, there is a very good affinity between the rootstocks of *C. congensis* and *C. canephora*. If *C. congensis* is grown on its own roots, it suffers markedly in drier areas and during years with drought,[17] possibly because it is adapted to growing in soils with a high moisture content. When *C. congensis* is grafted onto *C. canephora*, it presents good crop potential in Ivory Coast and India, and in favourable years the yields can be on a par with Arabica and Robusta.[17] The same authors report the following agronomic observations for the cultivation of *C. congensis* (on *C. canephora* rootstocks) in Sierra Leone.

According to Anthony and Le Pierrès,[17] the percentage of single-seeded fruits (so called pea-berry, or caracolis) is 18–19%. The weight of 100 beans (W100) is 11 g, sometimes reaching 15 g for exceptional genotypes. The conversion ratio between fresh cherry and green (clean) coffee is 5:1 (22.2%). The harvest is split into four or five passes (repeated picking intervals) but is sometimes undertaken in a single pass for some genotypes.

The same authors[17] reported the following agronomic observations for the cultivation *C. congensis* in Ivory Coast. Field study genotypes produced between 2.9 and 4.1 kg fresh cherry per tree, which represents between 0.63 and 1.33 kg of clean (green) coffee per tree per year, which translates to 800–1800 kg ha^{-1} of clean coffee under optimal planting density. Shade is not necessary for the cultivation of *C. congensis* in the Ivory Coast. Cheney[23] reported that in countries bordering the Equator it can be cultivated up to 800 m elevation.

Coffea congensis is generally reported as coffee leaf rust resistant (*Hemileia vastatrix*) in Ivory Coast and in Uganda.[31] This observation supports earlier reports that *C. congensis* is either highly resistant or completely resistant to coffee leaf rust.[23,24]

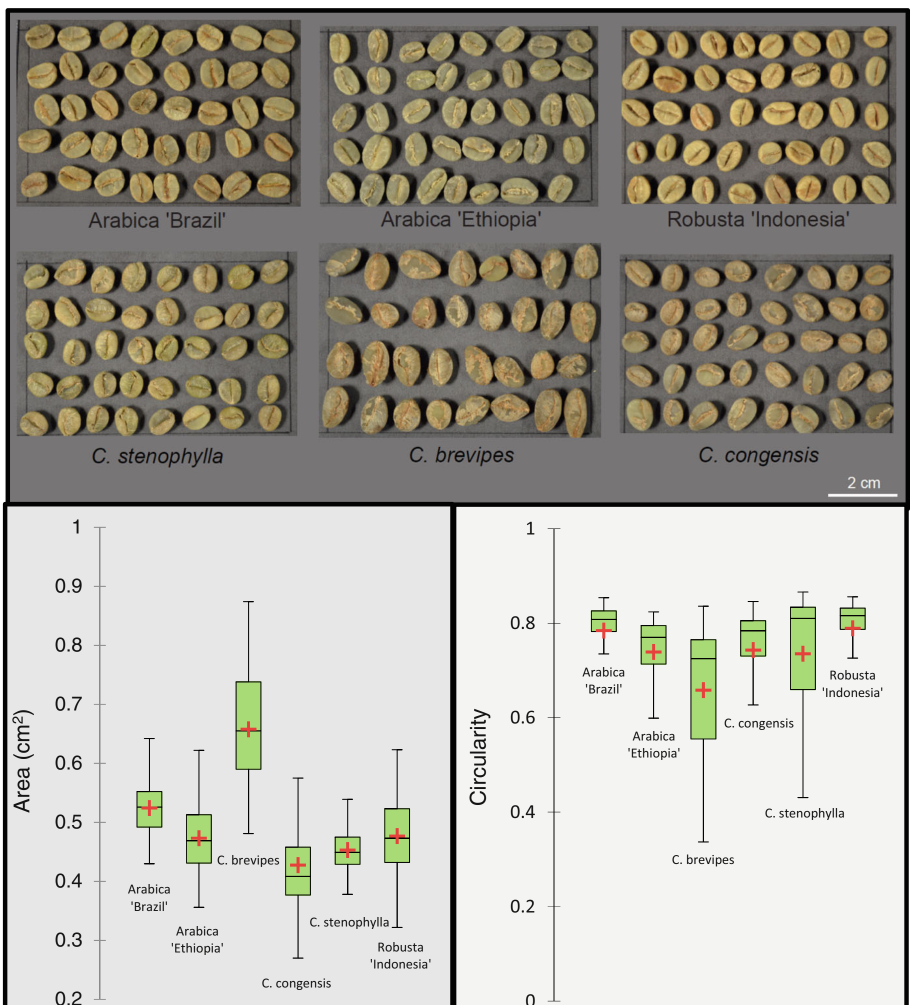
Information on the sensory properties of *C. congensis* is scant. Wellman[24] reported that it produced good-quality coffee, somewhat close to Arabica, but it is not clear whether this refers to the physical or sensorial quality. In Brazil, one report states that this species produces a coffee as good as Robusta and superior to 'Conilon', i.e. the *C. canephora* cultivar grown in Brazil.[32] *Coffea congensis* contains 1.08–1.83% dm caffeine and 8.15–8.77% dm of chlorogenic acids.[11]

Coffea congensis readily hybridizes with *C. canephora* (Robusta), resulting in fertile diploid hybrids,[14,24,33,34] which are mostly commonly known as *C.* × 'Congusta' and less frequently as *C.* × *crameri*[35] and *C.* × 'Conuga' for hybrids between this species and Uganda *C. canephora* (*C. congensis* × C. 'Ugandae').[24] *Coffea* × 'Congusta' has an improved amenability to cultivation compared to *C. congensis*[33] and is higher yielding.[24,33,36] A large grain size and strong branching habit has also been reported.[37] In hybridization studies, *C.* × 'Congusta' attains a fertility level equivalent to that of the intraspecific progeny of *C. congensis* and greater than that of *C. canephora*.[36]

The hybrids *C.* × 'Congusta' (or *C.* × 'Conuga') showed good resistance to coffee leaf rust in Brazil[38] and in Indonesia.[33] In Ivory Coast, *C.* × 'Congusta' was reported to have a poorly developed root system, and thus ill adapted to the soils and climates of the coffee-growing area of that country.[37]

Coffea brevipes

Coffea brevipes was named by Hiern in 1896 based on a sample collected in West Cameroon, by Gustav Mann in 1862.[39] It is indigenous to the central part of tropical West Africa, in Cameroon, Democratic Republic of Congo, Congo and Gabon[9,40] (http://apps.kew.org/wcsp/). It is a species of dense, humid evergreen forest, at elevations of 200–1450 m, but sometimes as low as



	Arabica 'Brazil'	Arabica 'Ethiopia'	Robusta 'Indonesia'	*C. stenophylla*	*C. brevipes*	*C. congensis*
W100 (g)	14.47	14.23	15.21	13.48	21.78	12.54
SD	0.21	0.38	0.64	0.11	0.22	0.63

Figure 2. Seed weight and morphology of three coffee species, *C. brevipes*, *C. congensis* and *C. stenophylla* (bottom) compared to (top) Arabica ('Brazil' and 'Ethiopia') and Robusta ('Indonesia'). The scale bar represents 2 cm (see Supplemental S4). Average weight of 100 green coffee beans (W100) in grams. Area (cm^2) and circularity (a value of 1 equates to a perfect circle) of the green beans, as measured by image analysis equipment (software ImageJ/Fiji).

80 m.[9,22,40] According to Burkill,[30] *C. brevipes* is used as wild-sourced, local coffee beverage species in tropical West Africa. To our knowledge, this species has never been the subject of a sensory evaluation; its cup quality has not been recorded. Literature relating to this species is largely limited to botanical characterization.[21,26,41] *Coffea brevipes* is a small tree (often no more than 1–2 m high) with obovate leaves, possessing a distinct leaf tip, and red fruits approximately the same size as *C. arabica*.[26,41] Molecular phylogenetic studies reveal that *C. brevipes* is closely related to *C. canephora* and *C. congensis*.[27-29] *Coffea brevipes* contains 2.36–2.96% dm caffeine and 10.40–12.30% dm of chlorogenic acids.[11] Very small-scale cultivation of *C. brevipes* started in Cameroon in 2019 (A Davis, pers. observ.).

Coffea stenophylla

Coffea stenophylla is endemic to Ivory Coast, Sierra Leone and Guinea,[42] but is probably also indigenous in Liberia. It occurs in the few remaining humid forests of the aforementioned countries, at relatively low elevation (~400 m). It has the western-most extension of all *Coffea* species[5,9] (Fig. 1[5]). A full account of its botanical and cultivation history is given by Davis *et al.*.[3,42] In Ivory Coast, Berthaud[22] found it in the west and east of the country and noted the very disjunct distribution of this species, especially in the west of the country where populations are only found on hilltops, separated from each other by about 50 km.

Coffea stenophylla is easily recognizable by its black or violet-black fruits (when ripe), as opposed to red (rarely yellow or pink) in Arabica and robusta. The leaves can be very narrow, although this is not a universal feature, and the flower parts are in multiples of six to nine (e.g., nine corolla lobes) as opposed to multiples of five in *C. arabica* and *C. canephora*.[42] It is classified as Vulnerable under the criteria of the IUCN Red List of Threatened Species (https://www.iucnredlist.org), due mainly to rapid deforestation.[3] During the late 19th century, *C. stenophylla* was widely cultivated in Upper West Africa and exported to Europe.[42] The almost total abandonment of *C. stenophylla* in the early 20th century has been put down to the widespread introduction and uptake of *C. canephora* (Robusta) coffee, which corresponds with the demise of *C. stenophylla* cultivation[42] but lower global coffee prices during that time may also have played a role.[43] Several historical references indicate that *C. stenophylla* has an excellent flavour.[42] Modelled data show that it has similar mean temperature and precipitation requirements to *C. canephora* and *C. liberica*, but with and a mean annual temperature requirement 6.2–6.8 °C higher than *C. arabica*.[5] A basic overview of seed chemistry for *C. stenophylla* is given in Davis *et al*.[5] *Coffea stenophylla* contains 2.05–2.43% dm caffeine and 6.76–9.39% dm chlorogenic acids.[11]

Seed characteristics

The coffee seeds of all five species examined possess a groove (invagination) on the flat (ventral) surface of the seed, as in all other coffee species.[44] We observed that for *C. arabica*, *C. canephora*, *C. congensis* and *C. stenophylla* this groove is rather straight, but in *C. brevipes* the groove is sinuous and rarely central (Fig. 2).

Coffea congensis and *C. stenophylla* (12.54 and 13.48 g, respectively) have a lower weight of 100 healthy green beans (W100), compared to *C. arabica* and *C. canephora* (14.23 and 15.21 g, respectively) while *C. brevipes* presented the largest W100 (21.78 g) (Supplemental S4). The conversion percentage/ratio (out-turn) between cherry (fresh weight of fruits) and clean (green) coffee (dry weight of beans without parchment) is between 14% and 18% (5.5–7.1:1) for *C. arabica*, *C brevipes* and *C. stenophylla*, and 20–23% (4.3–5:1) for *C. canephora* and *C. congensis*. The conversion rate for *C. congensis* is reported as 22.2% (4.5:1),[17] which falls within the range we found here (20–23%). Our results indicate that *C. stenophylla* and *C. brevipes* have approximately the same amount of pulp as *C. arabica*, while *C. congensis* and *C. canephora* have less. This factor is likely to have a bearing on post-harvest processing methods: *C. stenophylla* and *C. brevipes* should be treated more like *C. arabica*, whereas *C. congensis* should be treated like *C. canephora*.

Sensorial analysis

The analysis of variance on the variables studied (Supplemental S5) indicates low scores that result in no significant differences (Tukey's test, $P < 0{,}05$) between species, independent of roast level, for the attributes sourness, greeny, metallic, phenolic, rotten, and smelly (Supplemental S5). For the attributes of olfactory intensity, acidity, bitterness, astringency, body, fruity, harsh, earthy, burned, we found statistically significant differences between samples (Supplemental S5). The sensory attributes for the medium roasts are shown in Fig. 3. The largest amplitudes are found for the fruity attribute which is strongly correlated with the final quality ($r = 0.97$). The fruitiest samples are the Arabica 'Ethiopia' (scores 6.6–7) and *C. stenophylla* (scores 4.4–5.2).

The ascending hierarchical classification (AHC) shows a classification of the species (Fig. 4). There were three distinct groups that were significantly different. The Arabica 'Ethiopia' roasts formed a coherent group. A second group was formed by the three roast levels for *C. stenophylla*, and *C. brevipes* and *C. congensis* at light

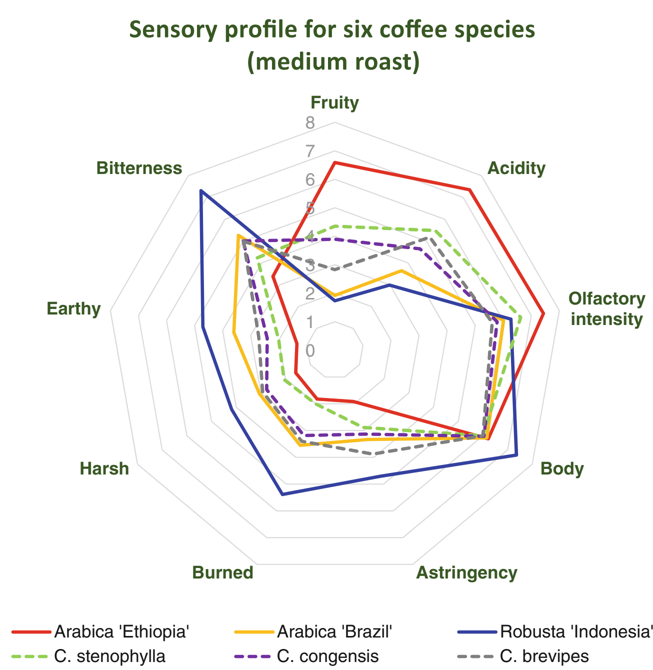


Figure 3. Radar diagram representing the main sensory attributes of six coffee samples. The graph represents the results obtained when the six coffee species were tasted by the cup at medium roast (using our sensory protocol). The three control species are shown as a solid line (Arabica 'Ethiopia' (red), Arabica 'Brazil' (yellow), Robusta 'Indonesia' (blue)), and the three wild species evaluated are represented by a broken line (*C. stenophylla* (green), *C. congensis* (purple) and *C. brevipes* (grey)). The first four criteria (clockwise from the top (fruity, acidity, olfactory intensity and body) are positive for coffee quality; the other five (astringency, burned, harsh, earthy and bitterness) are usually negative (see Supplemental S5).

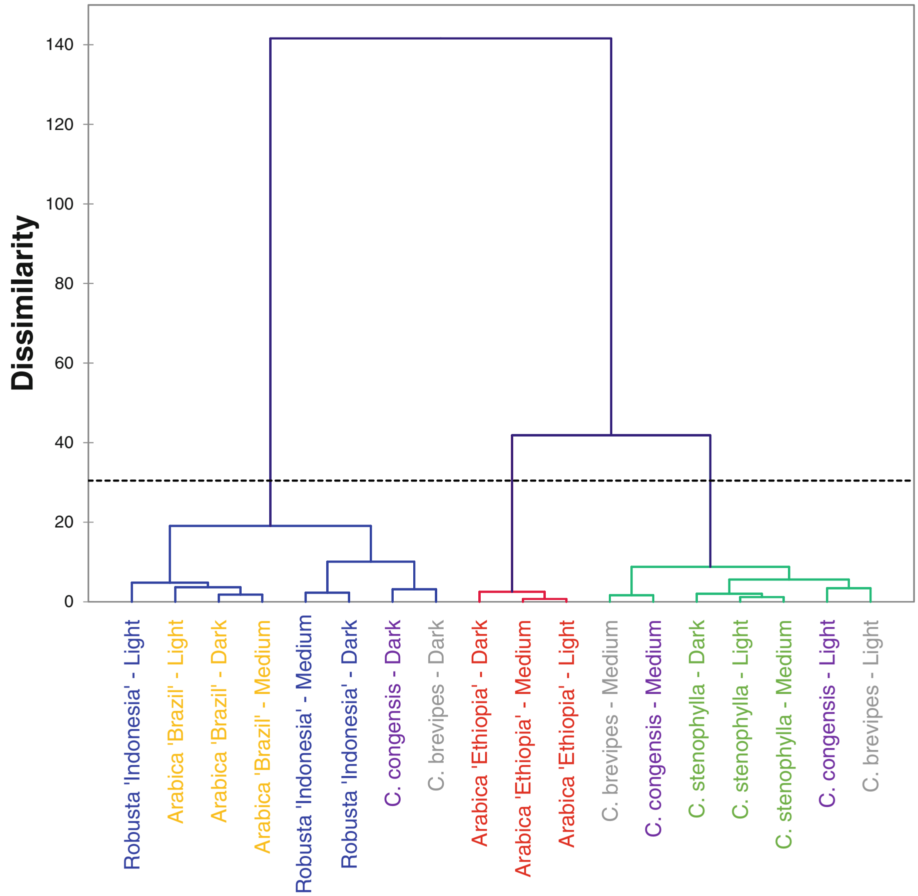


Figure 4. Ascending Hierarchical Classification (AHC) performed on the sensory attributes of six *Coffea* species samples. Above the dotted line, the groups are significantly different, while below the dotted line they are not (the two groups in blue text).

and medium roasts. Finally, a third group was formed by Robusta 'Indonesia' and Arabica 'Brazil' at all three roast levels, and *C. congensis* and *C. brevipes* when the roast was dark.

As to the questions 'Is this Arabica coffee?' and 'Is this Robusta coffee?' 98% of the jury classified the Arabica 'Ethiopia' as an Arabica-like coffee, regardless of the degree of roasting (Fig. 5). Regarding the Arabica 'Brazil', 51% of the jury classified it as an Arabica-like coffee and 47% as a Robusta-like coffee. For the Robusta 'Indonesia' 6% of the judges classify it as an Arabica-like coffee and 94% as a Robusta-like coffee (Fig. 5).

Our sample of *C. stenophylla* was considered as an Arabica-like coffee by 83% of the judges, and as a Robusta-like coffee by 2% of the judges (Fig. 5), which is similar to a previous evaluation (81% and 2%[5]). *Coffea brevipes* was also identified as Arabica-like by 69% of the judges, and less so as Robusta-like (12%) (Fig. 5). *Coffea congensis* was identified as Arabica-like by 46% of the judges and Robusta-like by 27% (Fig. 5). More than 80% of the judges considered that *C. brevipes* (98%), *C. congensis* (88%) and *C. stenophylla* (82%) could be commercialized and 30%, 52% and 41% (respectively) detected that they were tasting a new 'coffee' beverage (Fig. 5 and Supplemental S6).

The judges also freely described the samples with reference to open comments (Fig. 6 and Supplemental S7). The Arabica 'Ethiopia' sample was unanimously perceived as a floral and fruity coffee (Fig. 6). The *C. stenophylla* sample ranged across herb-like, vegetal, floral and fruit, with a broad range of fruit notes, like Arabica 'Ethiopia', and was also spicy, sugary and sweet (Fig. 6). Arabica 'Brazil' was scored by the judges as having notes that ranged, on the CIRAD Coffee Flavour Wheel(R), from herb-like to sugary. Robusta 'Indonesia' was unanimously perceived as having smoky, roasted and charcoal notes (from earthy to roasted on the CIRAD Coffee Flavour Wheel(R)). When *C. congensis* and *C. brevipes* were dark roasted they were rated like Robusta 'Indonesia' due to the burned attributes (Supplemental S5). On the other hand, when light or medium roasted, *C. brevipes* has the herb-like or vegetal notes as detected in *C. stenophylla*. The opinions concerning the *C. congensis* sample, when light or medium roasted, were very contradictory. Moreover, several judges were disconcerted by this coffee and did not know how to situate it on either the SCA Taster's Flavor Wheel[14] or CIRAD Coffee Flavour Wheel(R).

The brief narrative evaluation of the second sample of *C. brevipes* (cultivated in Cameroon), evaluated using the SCA protocol, was as follows: 'Fragrance sweet, fruits a little over-ripe. In the cup sweet and clean, simple. In the cup no obvious fruitiness or acidity present. Dark chocolate, woody notes, some savoury notes, hints of floral. "Gentle Robusta" dark, heavy notes, but without harshness and excessive bitterness' (E Chodarcevic, pers. comm.). In broad terms, these observations correspond well with the main sensory analysis (Fig. 6).

DISCUSSION

Understanding the sensorial quality and characteristics of a coffee species is an essential component of coffee's commercial

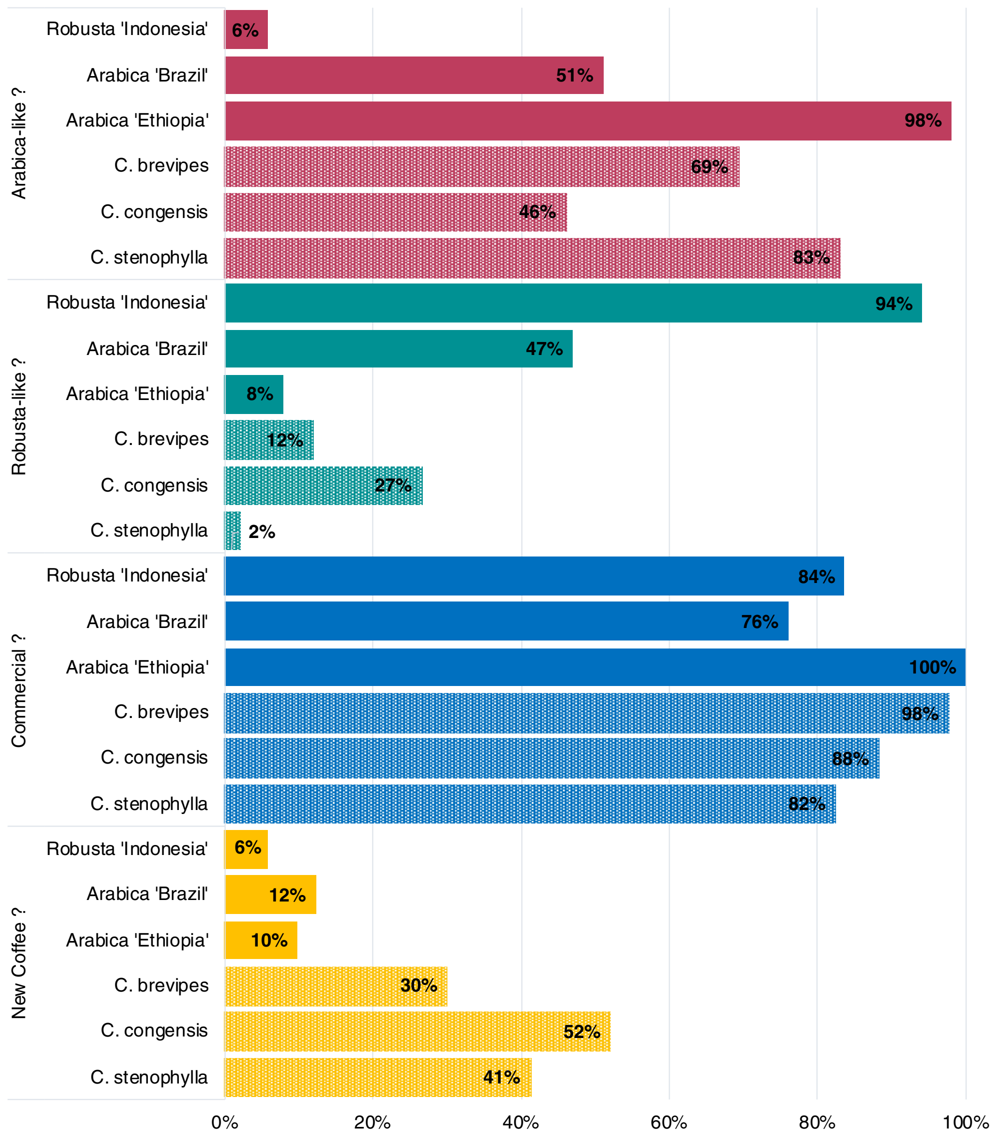


Figure 5. Four additional questions asked during the sensory evaluation protocol. From top to bottom, the questions asked were: Is this Arabica coffee? Is this Robusta coffee? Could this coffee be commercialized? Is this coffee new? The 17 judges answered yes or no to these questions for all three roast samples (n = 51 answers). The percentage of positive response s is indicated in the colour bars without pattern for the three control species: Robusta 'Indonesia, Arabica 'Brazil' and Arabica 'Ethiopia' or with pattern (white dots) for the three wild species studied: *C. brevipes*, *C. congensis* and *C. stenophylla* (see Supplemental S6).

suitability and market potential, which is required in addition to agronomic assessment and value chain functionality. In addition, understanding the sensory properties of a specific coffee species is of considerable value when it comes to breeding across species using hybridization (interspecific crosses). For example, when breeding for improved agronomic performance (such as resilience to drought), the sensorial properties need to be considered to ensure that the resulting coffee satisfies consumer preferences.

Coffea congensis

The sensory quality of *C. congensis* was superior to that of the Robusta 'Indonesia' sample, and thus potentially superior to commodity-level Robusta (*C. canephora*). Using a light or medium roast, the sensory quality was superior to that of the Arabica 'Brazil' sample and thus potentially superior to lower-quality commodity Arabica. *Coffea congensis* may thus have the potential for improving the sensory profile of *C. canephora*. Indeed, the flavour of the hybrid *C.* × 'Congusta' (*C. congensis* × *C. canephora*), provides an improvement on the traditional Robusta flavour profile (A Davis, pers. observ.). The improvement in *C.* × 'Congusta' is no doubt due to the inheritance of sensory positive attributes (see above) transferred via crossing. However, the cup quality of *C. congensis*, although better than that of *C. canephora*, is not akin to *C. arabica*, even after backcrossing with this species, because it lacks acidity and flavour complexity.[45]

Coffea × 'Congusta' promises improved agronomic performance over *C. congensis*, due to hybridization with *C. canephora*. *Coffea congensis* may provide an agronomic advantage (e.g., improved yield) over *C. canephora* in flood-prone areas or in locations that suffer from seasonally saturated soils, as in Madagascar.[34] Farmers growing the hybrid report (to A Davis,

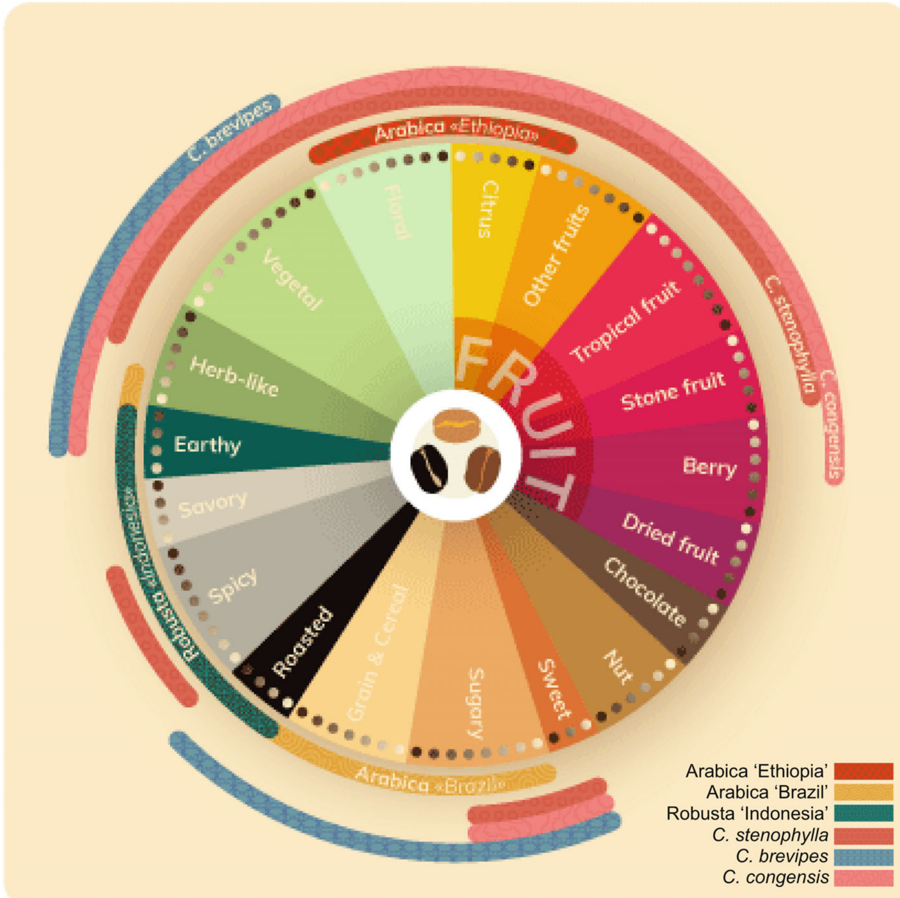


Figure 6. Schematic representation of the main sensory attributes of three wild coffee samples (*C. brevipes*, *C. congensis* and *C. stenophylla*) and commercial coffee samples (Arabica 'Ethiopia', Arabica 'Brazil' and Robusta 'Indonesia'). Representation on a Cirad Coffee Flavour Wheel. The main sensory attributes are based on open comments given by the judges at light and medium roast intensities (see Supplemental S7).

pers. comm.) that the soil moisture requirements are higher than *C. canephora*.

Coffea brevipes

This species has seeds (coffee beans) that approach the size and dimensions (granulometric characterization) of large-seeded *C. liberica*, which may confer both advantages (e.g., over the small, more rounded seeds of *C. canephora*) and disadvantages (e.g., issues with size grading and post-hulling processing). This species presents a sensory profile superior to our *C. canephora* sample from Indonesia (Robusta 'Indonesia') and superior to our *C. arabica* sample from Brazil (Arabica 'Brazil') when the roasting conditions are light or medium. *Coffea brevipes* may have the potential to form fertile diploid hybrids with *C. canephora*, given the close phylogenetic relationship between these species.[29,44] In this case, the aim of hybridization would be to improve sensory and seed characteristics. Indeed, the use of *C. brevipes* for the improvement of *C. canephora* was suggested by Campa *et al.*,[11] based not on sensory data but on the higher trigonelline content of *C. brevipes*. The genome sizes of *C. brevipes* and *C. canephora* (and *C. congensis*) are very similar.[46,47] We have no indication on the productivity (yield) for *C. brevipes*, although it appears to be on the low side (A Davis, pers. observ.). Crossing with *C. canephora* may improve flower and fruit number per shoot node (and thus per tree), robustness and vigour, traits which, when combined, are likely to improve yield.

Coffea stenophylla

Of the three species studied, *C. stenophylla* is closest in its flavour characteristics to *C. arabica*, and indeed has an Arabica-like flavour;[5] these species share some qualitative and quantitative chemical characteristics, including caffeine.[5,10] We demonstrate here that the physical appearance and dimensions of the seeds (coffee beans) are also like that of *C. arabica* (Fig. 2), although the unroasted colour is different. The sensory quality of *C. stenophylla* was closer to our specialty *C. arabica* sample from Ethiopia (Arabica 'Ethiopia'), rather than our commodity sample (Arabica 'Brazil'), with high scores for fruity, floral notes, and sweetness, as reported in Davis *et al.*,[5] which are among cuppers' and buyers' favourite coffee flavour and aroma attributes.[48] These characteristics usually drive a higher purchase price. *Coffea stenophylla* originates from a hot, tropical climate, and has a modelled mean annual temperature requirement 6.2–6.8 °C higher than *C. arabica* (which originated from a cool, tropical climate), even under equivalent rainfall conditions.[5] It is noteworthy that in the collection of the Reunion Island (BRC *Coffea*), *C. stenophylla* appears to be more productive than all the others coffee species being grown there, except *C. canephora* (T Joët, pers. comm.). Under good agronomic conditions with deep, quality soils, this species can probably be grown in many *C. arabica*-producing countries, but at higher temperatures (and probably lower elevations). Based on climate data and field observations,[5] *C. stenophylla* can be grown in areas where only *C. canephora* and *C. liberica* are currently farmed. Under projected global temperature increase,[49] this species could be an option for the replacement of *C. arabica*, where high-quality coffee is required. Resistance to coffee leaf rust is said to be a feature of *C. stenophylla*, with either high[5,50] or total[17] resistance reported. Nevertheless, it is important to corroborate reports and observations of agronomic performance, leaf rust resistance and climate resiliency, by setting up agronomic and agroclimatic trials under contrasting edaphoclimatic conditions. It is likely that further crop development work will be required for *C. stenophylla*, before being fully commercialized. The canopy density and size of the mature tree are comparable to those of *C. canephora* (Robusta type) and thus planting densities should be similar. *Coffea stenophylla* crosses with *C. canephora* in the diploid state but the fertility and productivity of the F1 hybrids are low.[36] On the other hand, crossing *C. stenophylla* with *C. liberica* should produce relatively fertile and vigorous hybrids.[36] Robust and vigorous diploid hybrids have been observed but their fertility and productivity have not yet been reported.[5]

CONCLUDING REMARKS

It should be noted that are results are indicative for each species, but may not completely represent the total sensorial variability within these species. Our data show that the three species under study – *C. brevipes*, *C. congensis* and *C. stenophylla* – have the potential beverage quality required for commercialization, particularly *C. stenophylla* and *C. congensis*. The sensory characteristics of *C. congensis* surprised the expert jury because this coffee does not match the standards of either Arabica or Robusta coffees. For this reason, it cannot be correctly located on the SCA Coffee Taster's Flavor Wheel[18] because the flavour notes found are not normally associated with beverage coffee. The flavour profile of *C. congensis* is promising and could appeal to consumers in the search for new coffee flavour experiences. The flavour of *C. stenophylla* is less disconcerting since it is like Arabica, i.e. floral and fruity, with only vegetal notes and a sweet taste, but our survey shows that it could provide differentiation compared to *C. arabica*.

Before adoption on a large scale and entering the food basket of *Homo sapiens*, it will be necessary to test these species at scale in order to verify their potential both agronomically and in terms of consumer demand. We know that *C. congensis* and *C. canephora* may be crossed with each other in the diploid state, and probably also both with *C. brevipes*, given their close phylogenetic relationships. Crossing with Arabica may also be possible, via tetraploidization of the diploid species parents. These interspecific hybrids seem capable of providing altered sensory profiles and may provide hybrids adapted to different climatic and agronomic conditions.

All three species have been greatly reduced over their indigenous ranges due to deforestation and other forms of land use change,[3] particularly *C. stenophylla*, and this should alert us to the inherent fragilities of biodiversity, and the dangers of reducing infraspecific genetic diversity, which lessens the crop potential of any species, or in the worst case may threaten the species in its entirety.

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SUPPORTING INFORMATION

Supporting information may be found in the online version of this article.

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