

Participatory identification of cashew (*Anacardium occidentale* L.) promising genetic resources in Ivory Coast

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Abstract

Ivory Coast ranks first and third in the world in cashew nut production and processing, respectively. Despite this performance, the profitability of Ivorian cashew orchards remains low, due mainly to a lack of improved varieties and the use of inappropriate farming practices. To address this problem, farmer-participatory selection of promising trees was conducted for three consecutive years (2019–2021) in four administrative regions covering the main cashew production zones of the country. Investigations were carried out on 121 cashew trees using eight quality traits indicated by farmers, six yield components and two traits of industrial interest. High phenotypic variability was noted for most of the traits analyzed (coefficient of variation > 25% for 12/15 traits). A total of 42 trees was identified as promising trees. Considering the yield trait, 9, 22, and 11 trees were classified as good (15–20 kg nut/year), best (21–30 kg nut/year), and elite (> 30 kg nut/year), respectively. From the combined analysis of quality criteria, five trees (L45, A15, R22, J27, and H23) were proposed for local distribution to farmers. Five trees with good industrial qualities in addition to interesting yields (17.28–28.95 kg nut/year) have been proposed for cultivation for double purposes: A45 and G14 for nut and beverages; and A34, A41, F21, and L22 for nut and the cashew nut shell liquid. The trees G27, I11, I12, and G24 with high sugar contents (37.71–26.24 Brix) can be grown for beverages. Phenetic analysis showed only two distinct groups, suggesting a narrow genetic basis of cashew trees in Ivorian orchards. Additional studies and means for a better valorization of these genetic resources are suggested.

Introduction

Cashew tree (*Anacardium occidentale* L.) is a tropical crop (native from Brazil) with multiple uses which can contribute to several food and industry sectors (Nyirenda et al. 2021; Chen et al. 2023; Nunes Lemes et al. 2023). With around 1,095,000 tons of nuts produced in 2022 (www.fao.org/faostat/fr/#data/), cashew tree ranks third among the nut crops after almond (1,477,000 tons) and walnut (1,1556 tons). Cashew nuts are consumed worldwide in various food forms (roasted, fried, salted, sugared snacks) and used in confectionery and bakery (Chen et al. 2023). These uses of cashew nuts are driven by their nutritional composition, mainly their content in vital minerals which are seldom found in daily diets. In addition, the pericarp of cashew nut contains a dark brown viscous liquid (cashew shell liquid or CNSL) which is a very important agricultural byproduct. Indeed, CNSL is an industrial raw material useful for the manufacture of numerous products such as friction dust for brake linings and clutch facing, coatings, adhesives, pharmaceuticals, surfactants, pesticides, etc. (Mubofu and Mgaya 2018; Sharma et al. 2020; Nyirenda et al. 2021).

In recent decades, the market and commercial values of cashew have been increasing steadily. The world production which was 2.3 million tons in 2018 (Zheng and Luo 2013) reached 3.84 million tons in 2021 (Global Cashew Council; www.nutfruit.org). This increase is mainly due to a growing global demand for the cashew nut, driven by its various uses.

Despite its social and economic importance, in the main nut-exporting countries, cashew is produced in inappropriate farming systems, which is a real challenge for its sustainability (Dendena and Corsi 2014; Monteiro et al. 2015; Danso-Abbeam et al. 2021). In most of these countries, cashew farming is done in extensive systems, with unsuitable technics and inefficient equipments (Catarino et al. 2015). Cashew chain value is still characterized by a significant lack of knowledge, due to a loosely structured research framework and the lack of integrated research programs. Therefore, smallholder farmers face major constraints including access to high yielding genotypes, training, and lack of investment in processing. Apart from Brazil and India, where the average yields can reach one ton per hectare (Oliveira et al. 2006; Bhat et al. 2010; Nayak and Muralidhara 2019; Rege and Lee 2022), in most nut producing countries, the yield of raw nuts does not reach 600 kg/ha (Aliyu and Awopetu 2011; Olubode et al. 2018). One of the main factors behind low yields of cashew orchards is the lack of high yielding varieties. Few producing countries have formally confirmed improved varieties (Masawe 2006; Bhat et al. 2010; Masawe et al. 2017; Matos Filho et al. 2019; Nayak and Muralidhara 2019). This challenges cashew breeders because high-performance varieties are essential for the increase of orchard yields (Mishra et al. 2016; Ahmed et al. 2017; Tufa et al. 2019).

Since 2015, Ivory Coast is the first world producer and exporter of raw cashew nuts with around one million tons in 2021 and 2022. In this country, cashew is one of the cash crops that contributes significantly to poverty alleviation and to the prevention of social conflicts due to the land crisis in rural regions (Colin and Ruf 2011; Ruf 2018; Ruf et al. 2019). For instance, cashew farming in the Northern and Central regions contributes to reducing migration to the most densely populated forest zones of the South. In Ivory Coast the crop is grown by 450,000 producers on 1.4 million hectares using unselected landraces. The average yield of Ivorian cashew orchards is low, around 560 kg/ha, against 1–2 t/ha in Brazil, India, or Vietnam. Cashew breeding and improved crop husbandry are therefore among the prerequisites for the sustainability of its production in Ivory Coast.

Participatory breeding is necessary for rapid adoption of varieties, especially for low input cropping systems. Training farmers on the proper use of innovations is facilitated if they participate in determining the quality criteria for these innovations (Paltasingh and Goyari 2018; Shafiwu et al. 2022).

It has been hypothesized that since the first introduction of cashew in Ivory Coast in the 1950s, favorable gene combinations have taken place, which could result in the presence of high-performing genotypes in peasant orchards. So far, these genotypes remain unidentified despite the relative performance of the country in cashew production. In this study, farmer participatory varietal selection approach was used in the search of promising genotypes of cashew trees in different administrative regions covering three climatic zones of Ivory Coast.

Material and methods

Study area

The study was carried out in four administrative Regions of Ivory Coast (Bounkani, Folon, Baffing, and Indénié-Djuablin) belonging to three climatic zones (Fig. 1). Surveys and observations were carried out in cashew orchards from 11 villages. The localities targeted in the study are representative of the climatic zones in which cashew is produced in Ivory Coast. In most of the West African countries such as Ivory Coast, cashew cultivation is regularly practiced in ecological zones characterized by savannahs or forest-savannah mosaics (Dedzoe et al. 2001).

Indénié-Djuablin is in the tropical rain forest zone. Rainfalls are abundant (annual mean > 2000 mm) and average annual temperature is 28°C. Bafing Region is in Guinea savannahs zone. This zone is characterized by the transitional woodland savanna, with several blocks of semi-deciduous forests. Rainfalls vary from 900 to 1900 mm with an annual mean of 1250 mm. The annual average temperature is 27°C. Folon Region is in sub-Sudanian savannahs zone. The annual rainfalls in this zone vary from 800 to 1400 mm with an annual mean of 1200 mm, and the annual mean temperature is 27°C. The vegetation is the woodland savanna showing extended ranges of herbaceous areas. The Sudanian zone, where Bounkani Region is located, is characterized by rainfalls always lower than 1200 mm/year, with a long dry season (at least 6 months), and the annual mean temperature is 28°C.

Plant material

The plant material consisted of 121 cashew trees chosen by farmers as potential high yielding. The location of these trees is indicated in Table 1. The trees were observed throughout the cashew harvest period in Ivory Coast, from September to July for three years (2018/2019, 2019/2020, and 2020/2021). Trees were surveyed individually from the first flower panicle appearance to the fall of the last apple. The nuts were harvested each two days and weighted weekly. Trees with mean nut yields over the two first years below 15kg/ha were discarded from the survey of the third year. Such trees were considered as non-promising on yield basis.

Table 1
Code, localities of origin, geographic coordinates, and age of the 121 cashew trees

Code	Region	Locality	Geographic coordinate	Age
A11	Bounkani	Poliédouhô	09°18'00"N-02°54'13"W	13
A12			09°18'01"N-02°54'13"W	13
A13			09°17'59"N-02°54'10"W	13
A14			09°17'59"N-02°54'14"W	13
A15			09°17'59"N-02°54'16"W	13
A21			09°17'44"N-02°53'56"W	16
A22			09°17'43"N-02°53'50"W	16
A23			09°17'59"N-02°54'10"W	16
A24			09°17'59"N-02°54'13"W	16
A25			09°17'59"N-02°54'10"W	16
A31			09°17'39"N-02°53'59"W	19
A33			09°17'38"N-02°53'59"W	19
A34			09°17'48"N-02°54'09"W	19
A35			09°17'48"N-02°54'08"W	19
A41			09°16'56"N-02°54'18"W	19
A42			09°16'57"N-02°54'27"W	19
A43			09°16'56"N-02°54'16"W	19
A44			09°16'55"N-02°54'17"W	19
A45			09°16'55"N-02°54'10"W	19
B11		Niandégué	09°15'31"N-02°53'17"W	28
B24			09°15'12"N-02°53'58"W	22
B43			09°14'53"N-02°53'30"W	28
B44			09°14'50"N-02°53'29"W	28
B45			09°14'49"N-02°53'31"W	28
R19		Gnégnondouho	09°18'50"N-02°54'13"W	14
R21			09°18'24"N-02°54'26"W	14
R22			09°18'27"N-02°54'27"W	14
R23			09°18'29"N-02°54'27"W	14
E11	Indénié-Djuablin	Kouamé-Ziankro	07°02'17"N-03°25'02"W	09
E13			07°02'16"N-03°25'04"W	09
E21			07°02'03"N-03°24'58"W	23
E22			07°02'02"N-03°24'57"W	23
E23			07°03'00"N-03°24'54"W	23
E25			07°02'01"N-03°24'51"W	23
E31			07°02'39"N-03°25'11"W	16
E32			07°02'39"N-03°25'12"W	16
E33			07°02'40"N-03°25'15"W	16
E34			07°02'40"N-03°25'14"W	16
E35			07°02'39"N-03°25'13"W	16
E42			07°01'52"N-03°23'12"W	22
F11		Padiègnan	06°58'21"N-03°25'17"W	17

Code	Region	Locality	Geographic coordinate	Age
F12			06°58'19"N-03°25'29"W	17
F13			06°58'20"N-03°25'30"W	17
F21			06°59'03"N-03°26'13"W	25
F23			06°59'04"N-03°26'12"W	25
F24			06°59'04"N-03°26'13"W	25
F25			06°59'05"N-03°26'14"W	25
F34			06°59'16"N-03°25'11"W	22
F35			06°59'16"N-03°25'10"W	22
F42			06°59'16"N-03°25'15"W	20
F45			06°59'16"N-03°25'14"W	20
G12	Folon	Goulia	09°59'41"N-07°13'00"W	17
G14			09°59'43"N-07°13'02"W	17
G15			09°59'43"N-07°13'04"W	17
G21			10°02'11"N-07°13'07"W	22
G22			10°02'15"N-07°13'06"W	22
G24			10°02'12"N-07°13'11"W	22
G27			10°02'17"N-07°13'17"W	22
G33			09°59'51"N-07°10'21"W	27
H11		Tahara	10°09'33"N-07°06'52"W	14
H12			10°09'34"N-07°06'54"W	14
H13			10°09'37"N-07°06'50"W	14
H14			10°09'38"N-07°06'50"W	14
H15			10°09'38"N-07°06'51"W	14
H21			10°09'32"N-07°08'02"W	07
H22			10°09'34"N-07°08'37"W	07
H23			10°09'31"N-07°08'40"W	07
H24			10°09'32"N-07°08'41"W	07
H25			10°09'33"N-07°08'41"W	07
H26			10°09'33"N-07°08'36"W	07
H33			10°11'25"N-07°06'11"W	25
H42			10°11'07"N-07°06'11"W	19
H44			10°11'07"N-07°06'13"W	19
I12		Kouroulingué	10°10'19"N-07°17'42"W	14
I13			10°10'16"N-07°17'42"W	14
I21			10°10'12"N-07°16'55"W	19
I22			10°10'12"N-07°16'59"W	22
I24			10°10'14"N-07°16'46"W	14
I25			10°10'14"N-07°16'42"W	13
I27			10°10'10"N-07°16'45"W	19
I31			10°09'46"N-07°17'14"W	13
I33			10°09'45"N-07°17'20"W	13
I35			10°09'45"N-07°17'19"W	13
I36			10°09'44"N-07°17'18"W	13

Code	Region	Locality	Geographic coordinate	Age
I41			10°11'00"N-07°17'56"W	26
I43			10°11'00"N-07°17'53"W	26
J13	Bafing	Koro-Sanankoro	08°24'55"N-07°35'55"W	28
J15			08°25'01"N-07°36'04"W	21
J16			08°25'03"N-07°35'59"W	28
J21			08°25'25"N-07°35'42"W	14
J22			08°25'24"N-07°35'43"W	14
J23			08°25'21"N-07°35'46"W	14
J24			08°25'23"N-07°35'48"W	24
J25			08°25'23"N-07°35'46"W	14
J26			08°25'22"N-07°35'46"W	14
J27			08°25'25"N-07°35'44"W	24
J31			08°25'24"N-07°36'26"W	18
J32			08°25'23"N-07°36'27"W	18
J41			08°25'17"N-07°36'13"W	12
K15		Yaala	08°18'20"N-07°29'10"W	17
K23			08°18'40"N-07°29'00"W	18
K31			08°17'55"N-07°28'20"W	19
K35			08°17'49"N-07°28'20"W	19
K36			08°17'47"N-07°28'21"W	19
K41			08°18'42"N-07°28'06"W	12
K42			08°18'43"N-07°28'09"W	12
K43			08°18'42"N-07°28'10"W	12
L11		Soula	08°21'37"N-07°59'34"W	15
L12			08°21'38"N-07°59'35"W	15
L13			08°21'39"N-07°59'31"W	14
L14			08°21'40"N-07°59'29"W	15
L15			08°21'40"N-07°59'28"W	15
L22			08°20'45"N-08°00'22"W	12
L24			08°20'47"N-08°00'21"W	14
L33			08°20'46"N-08°01'20"W	11
L34			08°20'47"N-08°01'20"W	11
L42			08°21'02"N-08°01'23"W	17
L43			08°21'08"N-08°01'21"W	17
L45			08°21'08"N-08°01'22"W	20
L46			08°21'08"N-08°01'23"W	08
L47			08°21'06"N-08°01'22"W	07

Analysis of traits

In each Region, participatory rural appraisal-based method with 50–75 farmers (women and men) was used to gather local communities' knowledge of cashew tree quality criteria. This approach is mainly based on interviews, the use of multiple-choice question forms and on-farm observations (Gibbs 1987; Chambers 1994). Thus, 8 traits related to tree architecture, flowering and fruiting phenology, nut weight and size, and tree yield were indicated by farmers as the features best describing a promising cashew tree (Table 2). Six additional traits considered as yield components in cashew (Faluyi 1986; Aliyu 2006; Aliyu and Awopetu 2011) were examined to access the phenotypic diversity and the phylogeny relationships between trees. Apple sugar content, kernel output

ratio (KOR) and cashew nut shell liquid (CNSL) were determined on high yielding trees to evaluate their economic and valorization potentials. CNSL was extracted using Soxhlet technique as applied by Tyman et al. (1989). Measurements on trees were carried out using cashew descriptors (IBPGR 1986).

The classification of cashew genotypes among promising trees was realized according to nut yields of best varieties realized in Brazil (Hawerth et al. 2019), Tanzania (Masawe et al. 2017; Massawe and Kapinga 2023) and India (Nayak and Muralidhara 2019). We have thus classified the trees observed into four categories: non-productive (< 13 kg nuts per year), good (15–20 kg nuts per year); best (21–30 kg nuts per year), and elite (> 30 kg nuts per year). Trees producing at least 13 kg nuts per year were considered as promising.

Based on promising tree quality criteria indicated by farmers, timing, duration, and periodicity of production in a year were analyzed. Concerning the fruiting time, trees were qualified as early (fruiting peak before December), normal (fruiting peak between February and April) or late (fruiting peak after April). Three categories of tree were defined according to the fruit harvest period duration. Thus, trees for which at least 95% the fruit harvest period lasted 45 days, 46–60 days, and over 60 were termed short-duration, normal-duration, or long-duration fruiting, respectively. The trees were also qualified either as single or multiple fruiting (at least two fruiting episodes), based on the frequency of their annual fruiting.

Statistical analyses

The data collected were summarized into a matrix with descriptive statistics (minimum, maximum, year mean, standard deviation, and coefficient of variation) calculated for each trait. Dunnett's test for multiple comparisons was used to classify the cashew trees as non-productive, good, best, or elite.

Multivariate analyses were carried out using mean data to access phenotypic diversity and phylogeny relationship between trees. Prior to the multivariate analyses, the data average values were standardized [standardized data = (sample estimates-mean)/standard deviation] to reach the same scale for all the traits (Dagnelie 2011). Principal Components Analysis (PCA) was applied to analyze morphological variation and to assess differences between trees. PCA is particularly relevant to identify variables which contribute most to the value of each principal component. ACP application conditions were checked using Bartlett sphericity test and the Kaiser Meyer Olkin (KMO) index expressing the level of sampling adequacy (Kaiser 1974). Only variables for which KMO exceeded 0.5 were included in the PCA. Ascending Hierarchical Classification (AHC) was then performed to highlight the degree of resemblance and the phylogenetic relationships between the trees. Ward's method was used as agglomeration criteria and Euclidean distance as similarity index. Factorial Discriminant Analysis (FDA) was also carried out to identify variables contributing significantly to differentiation between groups highlighted by the AHC. The statistical significance of variables contribution was checked using Wilks' lambda test. R studio software (R Core Team 2022) was used to carried out all the statistical tests.

Table 2
List of traits analyzed on cashew trees and measurement approaches

SN	Trait (Unit)	Code	Measurement
1	Tree spread (m)	TSP*	Measured as the mean of the diameter in the two cardinal directions
2	Number of branches (count)	NBC	Count from the first branching
3	Tree height (m)	THT*	From ground to top of the tree
4	Fruiting timing	FTM*	Tree qualification based on the period in which the fruiting begins: early, normal, or late
5	Sex ration (%)	SRA	Ratio of hermaphrodite flowers to total number of flowers (hermaphrodite and male flowers), estimated on 12 flower panicles per tree, 4 on each side
6	Apple weight (g)	AWT	Measured as the mean of 60 apples, 15 from each side of the tree at mid-season
7	Sugar content (°Brix)	SCT	Measured using refractometer on 60 apples per tree
8	Fruit load (count)	FLO	Mean number of apples per panicle, counted on 10 panicles per tree
9	Fruit harvest period duration (day)	FHD*	Estimated as the duration of the period during which at least 95% of a tree's seasonal production is harvested
10	Number of fruiting episodes (count)	NFE*	Count of fruiting episodes in a 12-months period
11	Nut weight (g)	NWT*	Measured as the mean of the individual weight of 300 nuts
12	Kernel ratio	KRA	
13	Tree yield in nut (kg/tree/year)	TYD*	Total weight of nuts produced by a tree in a year
14	Kernel output ratio (lbs)	KOR	Measured using 1 kg raw nuts. $KOR = (Ra/100) \times 80 \times (1/0.4536)$ $Ra (\%) = (P2+P3/2)/P1 \times 100$ P1: weight of the nuts sample P2: weight of healthy kernel with skin P3: total weight of kernel + skins of nuts rejected at 50%
15	Graining (count)	GRN*	The number of nuts counted in a sample of 1 kg, three replicate per tree
16	Number of hermaphrodite flowers per panicle (count)	NHF	Mean number of hermaphrodite flowers per panicle, estimated on 12 flower panicles per tree, 4 on each side
17	Cashew nut shell liquid (g/100g fresh weight)	CNSL	Determined using the protocol of Tyman et al. (1989); three replicate per tree
* Traits indicated by farmers as features of a promising tree			

Results

Selection of promising trees

The minimum, maximum, mean, and coefficient of variation (CV) of the 15 quantitative traits measured are summarized in Table 3. Only three parameters (KRA, KOR, and CNSL) showed low CV (12.13–14.44%). High (25.00–50.00%) to very high (> 50.00%) CV were obtained for 12 traits, with very high CV for the yield and most yield components, including sex ratio, fruit load, nut yield and number of hermaphroditic flowers per panicle. Most of the trees' features preferred by farmers expressed high variability (Fig. 2).

Among the 121 cashew trees analyzed over three years, 42 showed the features of promising trees (nut yield greater than 13 kg/tree/year). Eight (19.04%) elite trees (> 30 kg /tree/year) were identified. Seventeen (40.48%) trees belonged to each of best and good categories. The majority (30 or 71.43%) of promising trees were the early type (fruiting peak before December). Only three trees (7.14%) were qualified as late type while the remaining 9 (21.43%) were identified as normal type.

Relatively high number (20 i.e., 47.62%) of the promising trees identified belong to the category with long-duration harvest period. Trees from types with short- and normal-duration harvest period were 10 (23.81%) and 12 (28.86%), respectively. Examples of trees with short harvest duration (within 45 days) are A14 and A21. I25 and K36 harvested from 46 to 60 days are representative of normal harvest duration trees, while I42 and K36 harvested for over 60 days are examples of trees with a long harvest duration. The trees harvested during short time were also mainly early fruiting. Most of the promising trees identified in this study (34, i.e., 80.95%) fruited once a year, whereas seven (16.67%) and one (2.38%) produced fruits two and three times respectively. Eight trees had nuts with very high weight (> 8 g), whereas this value was low (< 6g) in 20 trees. All the trees identified except one showed high values of kernel ratio (> 25%). Cashew nut shell liquid (CNSL) values reached 30 g/100 g FW in 34 trees (Table 4). Three promising trees (J24, J27, and K36) had high kernel output ratio (KOR > 48%).

Despite they are not part of trees qualified as elite or best, certain of studied trees presented very interesting features. This is for example the case of the tree G14 that produces apples and nuts weighting 148g and 15g, respectively. Consequently, this tree has a very low graining (62 nuts per kg of nuts). Tree H24 which was not among the promising ones, has a very short harvest time (26 days).

Table 3
Statistical parameters for 16 quantitative traits scored on 121 cashew trees

Trait (Unit)	Minimum	Maximum	Mean	Standard deviation	Coefficient of variation (%)
Tree spread (m)	4.93	16.20	9.68	2.20	22.72
Number of branches (count)	1.00	6.00	2.52	0.91	36.25
Tree height (m)	0.80	6.80	2.65	1.31	49.56
Sex ration (%)	0.01	0.36	0.10	0.07	70.16
Apple weight (g)	15.50	148.43	57.17	26.75	46.79
Sugar content (°Brix)	9.62	37.72	15.06	3.74	24.86
Fruit load (count)	1.00	10.00	3.85	1.97	51.07
Fruit harvest period duration (day)	21.00	113.00	60.46	22.26	36.82
Number of fruiting episodes (count)	1.00	3.00	1.19	0.43	36.49
Nut weight (g)	2.22	15.93	6.33	2.16	34.07
Kernel ratio	23.04	48.31	32.54	4.70	14.44
Tree yield in nut (kg/tree/year)	5.08	73.48	14.71	10.96	74.46
Kernel output ratio (lbs)	35.05	59.27	49.71	6.03	12.13
Graining (count)	62.00	328.00	174.83	54.00	30.89
Hermaphrodite flowers / panicle (count)	1.00	40.00	11.60	8.33	71.80
Cashew nut shell liquid (g/100 g FW)	23.04	48.31	32.54	4.70	14.44

Table 4
Performance features of the 42 promising cashew trees

Tree code	Mean ($\pm$ SD) or attribute															
	TSP	NBC	FTM	SRA	AWT	SCT	FLO	FHD	NFE	NWT	KRA	TYD	KOR	GRN	NHF	CNS
A11 ^E	10.05	3.00	Early	0.12 $\pm$ 0.02	39.91 $\pm$ 16.84	13.76	7.50 $\pm$ 0.71	42.00 $\pm$ 21.17	2.00	4.52 $\pm$ 0.80	34.04 $\pm$ 1.96	38.52 $\pm$ 3.92	59.27 $\pm$ 0.82	193.00 $\pm$ 9.90	18.33 $\pm$ 16.29	33.0 $\pm$ 0.9
A12	9.24	2.00	Early	0.08 $\pm$ 0.01	62.73 $\pm$ 0.00	13.39	2.50 $\pm$ 0.71	48.75 $\pm$ 19.40	3.00	6.66 $\pm$ 0.57	32.67 $\pm$ 0.00	21.10 $\pm$ 6.61	46.97 $\pm$ 0.00	155.00 $\pm$ 0.00	10.00 $\pm$ 4.00	30.9 $\pm$ 0.3
A15 ^E	8.39	3.00	Early	0.08 $\pm$ 0.06	41.87 $\pm$ 2.07	12.96	5.00 $\pm$ 3.46	24.33 $\pm$ 12.34	2.00	6.60 $\pm$ 0.93	33.49 $\pm$ 0.91	35.57 $\pm$ 6.80	55.89 $\pm$ 0.19	159.00 $\pm$ 5.66	10.67 $\pm$ 4.16	31.5 $\pm$ 0.3
A21	11.06	2.00	Early	0.06 $\pm$ 0.00	34.20 $\pm$ 0.00	10.62	4.00 $\pm$ 0.00	35.00 $\pm$ 9.90	1.00	4.84 $\pm$ 0.00	35.01 $\pm$ 0.90	20.67 $\pm$ 4.83	42.16 $\pm$ 23.43	195.00 $\pm$ 14.14	9.00 $\pm$ 1.41	30.8 $\pm$ 5.0
A25	8.82	2.00	Early	0.08 $\pm$ 0.01	41.30 $\pm$ 28.14	13.71	5.50 $\pm$ 2.12	74.50 $\pm$ 2.12	1.00	4.63 $\pm$ 0.24	36.51 $\pm$ 0.00	15.21 $\pm$ 3.05	35.05 $\pm$ 0.00	216.00 $\pm$ 0.00	7.00 $\pm$ 4.58	32.0 $\pm$ 3.0
A31	8.20	2.00	Early	0.02 $\pm$ 0.01	21.15 $\pm$ 8.27	15.95	4.67 $\pm$ 2.08	38.50 $\pm$ 4.95	1.00	3.89 $\pm$ 0.08	35.87 $\pm$ 0.00	16.71 $\pm$ 3.73	54.70 $\pm$ 0.00	260.00 $\pm$ 0.00	2.50 $\pm$ 0.71	25.7 $\pm$ 0.3
A34	9.19	2.00	Early	0.02 $\pm$ 0.09	31.48 $\pm$ 9.73	17.68	9.00 $\pm$ 0.00	57.50 $\pm$ 12.02	2.00	5.30 $\pm$ 1.94	33.55 $\pm$ 4.04	20.54 $\pm$ 2.70	51.03 $\pm$ 2.16	187.50 $\pm$ 7.78	3.00 $\pm$ 0.00	39.0 $\pm$ 2.3
A41	10.16	1.00	Early	0.09 $\pm$ 0.04	33.59 $\pm$ 1.78	15.14	5.67 $\pm$ 4.16	50.50 $\pm$ 21.92	1.00	4.58 $\pm$ 0.03	34.33 $\pm$ 3.27	21.45 $\pm$ 1.46	51.41 $\pm$ 1.44	202.50 $\pm$ 10.61	8.67 $\pm$ 3.51	36.3 $\pm$ 0.7
A43 ^E	10.57	4.00	Early	0.08 $\pm$ 0.03	27.05 $\pm$ 0.00	16.49	9.50 $\pm$ 3.54	62.50 $\pm$ 4.95	1.00	4.63 $\pm$ 1.63	35.31 $\pm$ 2.27	31.67 $\pm$ 10.89	49.37 $\pm$ 1.23	215.00 $\pm$ 79.20	8.50 $\pm$ 0.71	24.8 $\pm$ 1.0
A45	6.52	2.00	Normal	0.08 $\pm$ 0.02	15.68 $\pm$ 1.17	26.59	8.00 $\pm$ 1.41	50.50 $\pm$ 12.02	1.00	2.97 $\pm$ 1.09	37.66 $\pm$ 0.00	15.24 $\pm$ 4.68	58.01 $\pm$ 1.35	328.00 $\pm$ 0.00	6.00 $\pm$ 2.83	30.8 $\pm$ 0.7
E21	11.20	2.00	Early	0.30 $\pm$ 0.15	75.88 $\pm$ 13.61	14.04	4.33 $\pm$ 1.53	81.50 $\pm$ 21.92	2.00	7.04 $\pm$ 1.23	37.20 $\pm$ 8.10	17.02 $\pm$ 4.50	53.40 $\pm$ 9.86	141.50 $\pm$ 2.12	28.00 $\pm$ 11.14	32.3 $\pm$ 0.7
E22	13.89	2.00	Early	0.26 $\pm$ 0.13	46.75 $\pm$ 22.98	14.06	5.67 $\pm$ 2.08	100.00 $\pm$ 5.66	2.00	8.86 $\pm$ 1.52	37.59 $\pm$ 11.10	20.68 $\pm$ 7.47	47.34 $\pm$ 3.89	115.50 $\pm$ 2.12	18.67 $\pm$ 5.51	36.0 $\pm$ 3.6
E31	10.58	2.00	Early	0.28 $\pm$ 0.14	27.25 $\pm$ 0.35	13.43	5.33 $\pm$ 4.04	108.00 $\pm$ 16.97	2.00	5.42 $\pm$ 0.75	48.31 $\pm$ 0.00	20.71 $\pm$ 6.36	58.36 $\pm$ 0.00	185.00 $\pm$ 0.00	16.00 $\pm$ 6.08	33.5 $\pm$ 3.7
F21	15.41	2.00	Normal	0.03 $\pm$ 0.02	50.07 $\pm$ 14.23	14.18	3.67 $\pm$ 2.08	71.50 $\pm$ 4.95	1.00	8.53 $\pm$ 0.62	28.25 $\pm$ 0.26	23.58 $\pm$ 2.72	36.89 $\pm$ 15.42	117.00 $\pm$ 1.41	9.50 $\pm$ 6.36	38.0 $\pm$ 1.7
F34	10.33	2.00	Early	0.05 $\pm$ 0.02	44.48 $\pm$ 15.87	11.83	4.00 $\pm$ 1.73	79.50 $\pm$ 38.89	1.00	6.35 $\pm$ 1.15	32.12 $\pm$ 0.03	18.85 $\pm$ 2.40	54.49 $\pm$ 2.62	156.50 $\pm$ 7.78	12.00 $\pm$ 8.89	34.9 $\pm$ 1.8
F35	11.28	2.00	Early	0.04 $\pm$ 0.02	54.00 $\pm$ 14.38	12.40	5.67 $\pm$ 4.73	83.00 $\pm$ 33.94	1.00	6.94 $\pm$ 1.19	31.28 $\pm$ 0.00	15.66 $\pm$ 2.20	52.70 $\pm$ 0.00	144.00 $\pm$ 0.00	1.67 $\pm$ 1.15	31.2 $\pm$ 0.7
G14	11.26	2.00	Normal	0.09 $\pm$ 0.04	148.43 $\pm$ 18.37	16.64	2.33 $\pm$ 1.15	48.50 $\pm$ 14.85	1.00	15.93 $\pm$ 0.21	23.04 $\pm$ 0.00	17.28 $\pm$ 6.08	45.15 $\pm$ 0.00	62.00 $\pm$ 0.00	11.67 $\pm$ 2.52	38.1 $\pm$ 1.7
H23	14.25	2.00	Early	0.16 $\pm$ 0.08	90.64 $\pm$ 4.02	14.25	1.67 $\pm$ 0.58	36.50 $\pm$ 21.92	1.00	12.45 $\pm$ 4.26	27.47 $\pm$ 1.62	21.57 $\pm$ 18.49	42.33 $\pm$ 4.79	80.00 $\pm$ 5.66	18.67 $\pm$ 4.16	33.0 $\pm$ 1.0
H25 ^E	13.80	2.00	Early	0.16 $\pm$ 0.10	72.03 $\pm$ 14.52	13.80	6.00 $\pm$ 2.65	102.50 $\pm$ 14.85	1.00	6.32 $\pm$ 0.98	30.37 $\pm$ 2.79	31.73 $\pm$ 18.64	50.89 $\pm$ 1.64	160.50 $\pm$ 2.12	20.00 $\pm$ 8.72	23.7 $\pm$ 0.8

¹ Data were presented as an average of three years of study

Phylogenetic relationship between cashew trees

Tree code	Mean (± SD) or attribute																
	TSP	NBC	FTM	SRA	AWT	SCT	FLO	FHD	NFE	NWT	KRA	TYD	KOR	GRN	NHF	CNS	
I22	10.64	3.00	Late	0.03 ± 0.00	79.88 ± 16.02	10.30	4.33 ± 1.53	64.50 ± 4.95	1.00	6.57 ± 1.19	28.29 ± 0.02	22.30 ± 7.56	38.07 ± 13.87	152.50 ± 17.68	5.67 ± 3.79	29.0 ± 2.1	
I24	12.00	3.00	Late	0.04 ± 0.03	78.14 ± 0.19	11.59	3.00 ± 1.00	60.00 ± 11.31	1.00	5.57 ± 0.81	30.24 ± 1.18	21.05 ± 4.04	49.63 ± 4.78	176.50 ± 14.85	9.67 ± 5.86	32.9 ± 0.6	
I25	12.32	2.00	Normal	0.03 ± 0.03	45.25 ± 13.93	20.40	6.00 ± 1.00	80.00 ± 7.07	1.00	4.43 ± 0.06	37.54 ± 11.56	44.96 ± 11.44	49.76 ± 2.91	225.00 ± 36.77	6.33 ± 4.73	31.8 ± 2.5	
I33	9.71	2.00	Late	0.04 ± 0.03	90.46 ± 35.06	11.82	3.00 ± 1.00	76.50 ± 21.92	1.00	9.22 ± 0.45	27.85 ± 0.39	20.83 ± 0.83	47.50 ± 1.74	114.00 ± 2.83	13.33 ± 8.62	33.0 ± 1.0	
I35	11.77	3.00	Normal	0.12 ± 0.12	52.23 ± 2.82	13.70	4.67 ± 1.15	80.00 ± 16.97	1.00	7.62 ± 0.12	29.18 ± 0.00	22.27 ± 8.95	50.65 ± 0.00	133.00 ± 0.00	26.67 ± 19.09	32.4 ± 0.6	
I43	12.27	2.00	Late	0.03 ± 0.01	105.00 ± 11.46	11.98	2.33 ± 0.58	80.00 ± 16.97	1.00	7.27 ± 1.59	31.35 ± 1.60	16.28 ± 11.53	53.94 ± 2.95	139.00 ± 15.56	8.67 ± 6.43	35.6 ± 2.0	
J15	8.88	2.00	Early	0.09 ± 0.01	85.40 ± 0.00	13.21	7.00 ± 3.61	36.50 ± 2.12	1.00	6.56 ± 1.92	33.50 ± 1.32	24.43 ± 6.18	54.87 ± 7.92	192.50 ± 9.19	13.67 ± 7.23	31.9 ± 0.5	
J23	11.84	2.00	Normal	0.36 ± 0.26	42.54 ± 11.96	14.16	9.33 ± 2.08	40.00 ± 18.85	2.00	5.46 ± 0.57	33.17 ± 4.12	50.30 ± 7.30	56.07 ± 2.60	196.00 ± 7.07	28.33 ± 22.90	29.9 ± 3.8	
J24	12.64	3.00	Early	0.21 ± 0.18	28.48 ± 0.00	15.92	9.00 ± 0.00	50.50 ± 2.12	1.00	2.91 ± 0.84	29.04 ± 8.93	25.48 ± 8.23	48.85 ± 7.23	328.00 ± 35.36	13.67 ± 6.66	24.5 ± 0.5	
J27	12.87	2.00	Normal	0.04 ± 0.00	85.70 ± 0.42	15.60	2.33 ± 1.53	40.00 ± 12.73	1.00	8.56 ± 0.01	29.44 ± 1.41	25.28 ± 4.63	48.76 ± 2.96	124.50 ± 7.78	3.00 ± 1.73	33.3 ± 0.8	
K31	14.50	3.00	Normal	0.05 ± 0.01	35.42 ± 5.07	12.45	2.67 ± 2.08	50.50 ± 21.92	1.00	5.67 ± 0.16	31.67 ± 1.19	38.68 ± 14.89	55.03 ± 1.71	173.00 ± 1.41	7.00 ± 3.61	29.9 ± 1.3	
K36	9.75	2.00	Early	0.10 ± 0.04	44.39 ± 6.52	12.40	6.00 ± 2.00	59.00 ± 53.74	1.00	5.63 ± 0.71	28.96 ± 0.51	22.54 ± 7.26	48.44 ± 1.74	186.50 ± 6.36	8.33 ± 4.73	32.4 ± 1.7	
L12	11.84	2.00	Early	0.09 ± 0.07	29.25 ± 0.00	13.05	6.67 ± 5.03	38.50 ± 14.85	1.00	3.98 ± 0.46	29.24 ± 1.89	26.42 ± 8.64	51.87 ± 0.20	247.00 ± 24.04	10.00 ± 5.29	34.8 ± 0.7	
L13 ^E	10.14	3.00	Early	0.11 ± 0.09	31.97 ± 2.07	14.06	5.33 ± 2.89	45.00 ± 0.00	1.00	5.12 ± 1.02	28.97 ± 0.05	33.42 ± 9.27	50.70 ± 0.08	195.00 ± 0.00	8.00 ± 4.00	33.2 ± 0.1	
L22	10.19	3.00	Early	0.03 ± 0.02	46.29 ± 3.59	15.12	3.00 ± 1.73	50.00 ± 12.73	1.00	4.27 ± 0.42	29.17 ± 0.00	28.95 ± 21.93	49.09 ± 0.00	230.00 ± 0.00	3.33 ± 2.08	37.2 ± 2.9	
L33 ^E	11.75	2.00	Early	0.12 ± 0.10	47.76 ± 28.30	12.64	10.00 ± 2.83	65.00 ± 38.18	1.00	5.22 ± 1.65	46.87 ± 17.97	45.38 ± 22.51	52.22 ± 0.65	197.00 ± 9.19	11.50 ± 3.54	33.0 ± 0.1	
L34 ^E	11.00	2.00	Early	0.08 ± 0.02	93.02 ± 27.56	17.03	4.00 ± 1.41	75.50 ± 0.71	1.00	8.11 ± 2.62	29.23 ± 0.00	30.02 ± 15.21	38.27 ± 0.00	127.00 ± 0.00	15.00 ± 5.66	26.1 ± 0.4	
L43	13.28	3.00	Early	0.10 ± 0.04	81.92 ± 25.57	12.49	1.33 ± 0.58	103.00 ± 15.56	1.00	5.92 ± 0.48	33.21 ± 0.00	23.35 ± 20.95	53.99 ± 0.00	177.00 ± 0.00	12.00 ± 7.00	32.4 ± 1.7	
L45 ^E	11.98	2.00	Early	0.08 ± 0.06	63.68 ± 28.74	13.57	4.50 ± 4.95	53.50 ± 16.26	1.00	7.25 ± 2.74	31.13 ± 1.17	73.48 ± 8.06	51.09 ± 1.57	151.00 ± 22.63	6.67 ± 5.69	34.4 ± 0.8	
L46	9.64	2.00	Early	0.17 ± 0.06	74.43 ± 6.47	12.53	4.00 ± 0.00	113.00 ± 9.90	1.00	6.98 ± 0.00	33.14 ± 0.00	22.02 ± 8.74	51.88 ± 0.00	158.00 ± 0.00	21.67 ± 10.97	31.4 ± 1.7	

¹ Data were presented as an average of three years of study

Phylogenetic relationship between cashew trees

Tree code	Mean ($\pm$ SD) or attribute															
	TSP	NBC	FTM	SRA	AWT	SCT	FLO	FHD	NFE	NWT	KRA	TYD	KOR	GRN	NHF	CNS
L47	7.04	3.00	Early	0.13 $\pm$ 0.06	46.23 $\pm$ 21.74	12.20	5.50 $\pm$ 2.12	81.00 $\pm$ 55.15	1.00	6.32 $\pm$ 0.43	31.72 $\pm$ 5.88	22.05 $\pm$ 12.60	54.01 $\pm$ 6.56	167.50 $\pm$ 12.02	7.67 $\pm$ 5.13	35.3 $\pm$ 0.9
R22	10.62	3.00	Early	0.16 $\pm$ 0.11	79.52 $\pm$ 3.56	16.93	11.33 $\pm$ 6.51	47.00 $\pm$ 7.07	1.00	8.58 $\pm$ 0.58	31.44 $\pm$ 2.48	27.08 $\pm$ 7.26	36.69 $\pm$ 12.40	124.00 $\pm$ 5.66	29.33 $\pm$ 20.82	32.7 $\pm$ 4.3
R23	9.70	2.00	Normal	0.07 $\pm$ 0.04	59.32 $\pm$ 1.27	13.96	4.33 $\pm$ 2.52	64.00 $\pm$ 26.87	1.00	6.75 $\pm$ 0.71	28.27 $\pm$ 0.00	15.25 $\pm$ 3.72	50.85 $\pm$ 0.00	156.00 $\pm$ 0.00	10.33 $\pm$ 4.04	32.9 $\pm$ 0.1
¹ Data were presented as an average of three years of study																
Phylogenetic relationship between cashew trees																

Kernel ratio (KRA), kernel output ratio (KOR), graining (GRN), and cashew nut shell liquid (CNSL) were only measured on the 42 promising trees so they have been excluded from the analysis of the phenetic relationships. Correlation coefficients computed for all pairs of traits (data not shown) revealed a significantly positive value for apple weight (AWT) and nut weight (NWT): 0.82. To avoid redundancy, AWT have been discarded and PCA was performed using data from 11 traits. On the other hand, the global KMO value (0.61) was higher than 0.50 thus satisfying Kaiser Meyer condition.

The first four principal components (with eigenvalues > 1) loadings and their contributions are shown in Table 5. The cumulative contribution of the first (PC1) to fourth (PC4) component was 63.61% of the total variability among the 121 cashew trees, with 25.41, 15.66, 13.35, and 9.18% for PC1, PC2, PC3, and PC4, respectively. The number of hermaphrodite flowers (NHF), sex ration (SRA, and fruit harvest period duration (FHD), were positively and significantly correlated ($r > 0.69$) with PC1. These results indicated that PC1 was determined mainly by tree fruiting potential and duration. PC2 was correlated positively with the fruit load (FLO). The third principal component (PC3) was significantly correlated with tree yield (TYD) and spread (TSP), suggesting that this axis was characterized by traits contributing to the realization of yield. The projection of individuals (Fig. 3) in the principal plane (axis 1 - axis 2) visualized a high level of variability in the agronomic traits analyzed. However, this morphological diversity did not show evident distinction between cashew trees analyzed, based on the climatic zones where they are cultivated. Nevertheless, PC1 separated trees grown in Indénie-Djuablin region (mauve filled triangles) along its right side, in the negative part of PC2. PC2 separated trees from Bounkani (blue filled squares) because they are mainly placed on the positive part of the axis 2.

Table 5
Eigenvalues, percentage of variance, and loadings of the first four principal components based on 11 traits scored on 121 cashew trees

PCA parameters and traits	PC1	PC1	PC3	PC4
Eigenvalue	2.537	1.629	1.396	1.001
Variance (%)	28.187	18.102	15.508	11.120
Number of branches (NBC)	-0.155	-0.154	0.083	
Tree spread (TSP)	0.288	-0.145	0.694	
Tree height (THT)	0.617	-0.189	-0.366	
Sex ration (SRA)	0.850	0.116	-0.243	
Sugar content (SCT)	-0.360	0.284	-0.371	
Fruit load (FLO)	0.311	0.844	-0.039	
Fruit harvest period duration (FHD)	0.715	-0.277	-0.139	
Number of fruiting episodes (NFE)	0.370	0.144	-0.224	
Nut weight (NWT)	0.194	-0.549	0.411	
Tree yield (TYD)	0.271	0.621	0.625	
Hermaphrodite flowers (NHF)	0.709	0.051	-0.054	

Ward's agglomeration method used in AHC separated the 121 cashew trees into two groups (Fig. 4). One of the groups (Group 1) was composed of 44 trees (36.36%), seven from Bafing, 16 from Bounkani, one from Folon, and 20 from Indénie-Djuablin. This group contained 20 promising trees; and 45% (20/44) of trees from Indénie-Djuablin region, i.e. 86.96% of the trees from this group. The second group (Group 2) contained 77 trees (63.64%), with 28, 12, 34, and three from Bafing, Bounkani, Folon and Indénie-Djuablin, respectively. This group contained 22 promising trees, and is mainly composed of trees from Bafing (28, i.e. 80.00% of the trees from this region) and Folon (34, i.e. 97.14% of the trees from the region). The trees from Bafing and Folon regions represent 80.51% (62/77) of the individuals in group 2.

HAC confirmed the two groups (Mahalanobis $D^2 = 9.24$; $P < 0.0001$) highlighted by HAC. The percentages of correct classification of the 44 and 77 trees in Group 1 and Group 2 were 93.18% (41/44) and 98.70% (76/77), respectively. Factorial axis 1 represents 100% of the total variability and structures the trees into two distinct groups. Wilks' lambda test showed that five variables contribute significantly to the differentiation between these groups: tree height, number of hermaphrodite flowers, sex ratio, fruit load, and fruit harvest period duration (Table 6).

Table 6
Statistics of ascending hierarchical classification for five traits contributing significantly to discrimination of 121 cashew trees

Traits	Wilks' lambda	F	P
Tree height	0.72	46.46	< 0.0001
Sex ration	0.69	53.41	< 0.0001
Fruit load	0.74	41.95	< 0.0001
Number of fruiting episodes	0.71	47.76	< 0.0001
Number of hermaphrodite flowers	0.88	16.78	< 0.0001

Discussion

This participatory study documents comprehensively, the yielding performance and the industrial valorization potential of 121 cashew trees. The study is limited to 16 traits of practical interest for the farmers and the industries.

Significant variability was noted for the traits analyzed. Indeed, 12 of the 16 (75.00%) traits are characterized by high values of coefficient of variation (25–50%). Most of these traits are yield components, so they can be used in cashew breeding program (Chanda et al. 2018; Fasoula et al. 2020), as previously done for cocoa (Lachenaud and Oliver 2005; Lachenaud 2007), coffee (Akpertey et al. 2020, 2022), and tamarillo (Acosta-Quezada et al. 2011). The values of other traits observed in most of the promising trees identified, namely the nut weight, kernel ratio and precocity, correspond to farmers' quality criteria, thus facilitating their adoption (Lukurugu et al. 2022).

Of the 121 trees surveyed for three years, 30 were classified into good or elite categories. Nut yields of these trees are higher than those of the best varieties realized in Brazil, India, and Tanzania (Table 7). Indeed, our statistical simulations showed that, if planted at the recommended density in Ivory Coast (10 m x 10 m, resulting in 100 trees/ha), the 11 trees qualified as elites in this study would produce 3020 kg/ha (30,20 kg x 100) to 7348 kg/ha (73,48 kg x 100), with an average of 4124.81 kg/ha. At the same density of 10 m x 10 m (100 trees/ha), the six promising hybrid varieties obtained by Hawerorth et al. (2019) in Brazil and evaluated from 2010 to 2015 yielded on average 936.32 kg/ha (786.97–1,203.33 kg/ha). At 7–10 years, the yields of the five best cashew hybrid varieties developed in India vary from 1000.00 to 1500.00 kg/ ha (Nayak and Muralidhara 2019). About forty varieties of cashew are developed in Tanzania (Masawe et al. 2017; Massawe and Kapinga 2023). At a stand density of 100 trees per hectare, the six best hybrid varieties evaluated from 2010 to 2016 (Masawe et al. 2017) could produce a mean of 31.21 kg/ha, varying from 28.26 kg/ha to 38.20 kg/ha. Compared to these results, the 11 elite trees identified in this study represent a great achievement of the cashew breeding program in Ivory Coast. It is important to mention age which influences significantly yield in perennial crop species (Meena and Asrey 2018; Zhang et al. 2019). The 11 elite trees identified were between seven (H25) and 20 (L45) years old, with an average of 14 years. This mean corresponds to the period during which the yield of cashew tree reaches its maximum value (Dendena and Corsi 2014). The performances obtained in the present study are therefore reliable.

Table 7
Nut yield, nut weight, and kernel ratio of best cashew hybrid and genotypes from four countries

Genotype code	Origin ¹	Genotype type	Age (year)	Tree yield (kg/tree/year)	Nut yield (kg/ha) ²	Nut weight (g)	Kernel ratio (%)
CCP76xEmb.51 – 7	Brazil	Hybrid variety	3	12.03	1,203.33	7.03	.3
CCP76xHAC276/1–5			3	9.67	966.62	9.51	-
CCP76xHAC222/4 – 1			3	8.86	886.00	10.77	-
CCP76xEmb.51 – 6			3	8.39	838.67	9.05	-
CCP76xEmb.51 – 8			3	7.87	786.97	6.49	-
Vengurla-9	India	Hybrid variety	-	15.98	1,598	8.9	29.35
Jhargram-2		Clonal variety	7	13.50	1,350	9.20	32.00
BPP-10			-	14.90	1,490	8.10	19.30
BPP-11			-	14.70	1,470	6.80	28.00
Ganje-2			-	12.00	1,200	8.20	29.50
KN-2/9	Ivory Coast	Landrace	10	15.00	1,500	8.20	29.59
A15			13	35.57	3,557	6.60	33.49
H23			7	21.47	2,147	12.45	27.47
J27			24	25.28	2,528	8.56	29.44
L45			20	73.48	7,348	7.25	31.13
R22	Tanzania	Hybrid variety	14	27.08	2,708	8.58	31.44
C1-4			20	38.20	3,820	7.82	30.27
C15-2-26			20	31.39	3,139	6.69	30.94
C10-1			20	31.15	3,115	7.20	29.35
C15-4			20	29.45	2,945	6.84	31.83
C25-3			20	28.79	2,879	6.10	31.32
C15-2-8			20	28.26	2,826	6.66	33.07
AC4		Clonal variety	20	26.48	2,648	7.61	31.86

¹ Data concerning the varieties developed in Brazil, India, and Tanzania are from Hawerth et al. (2019), Nayak and Muralidhara (2019), and Massawe et al. (2017), respectively.

² Nut yields are based on a stand density of 100 trees per hectare, as recommended in Ivory Coast.

³ Data not published.

The classification based on the combination of the farmers' main quality criteria in decreasing order (nut yield, nut weight, kernel ratio, fruiting time, fruit harvest period duration) shows that L45, A15, R22, J27 and H23 are the five most interesting trees in terms of agronomic performances. These trees can be primarily distributed to farmers to create new high yielding orchards and to continue the selection of high performing genotypes. The G14 tree producing the biggest apples (148.43 g) can be grown for its fruit, whose content in sugar is also interesting (16.64 °Brix). Cashew nut shell liquid (CNSL) is a fluid from the pericarp of the cashew nut, composed of a mixture of phenolic compounds that have several applications in polymer based industries (Nyirenda et al. 2021). In addition to having interesting nut yields, five of the trees studied (A34, A41, G14, F21, and L22) have very high CNSL contents (39.03–36.34 g/100g FW). These trees can be cultivated both for nuts and CNSL production.

Although they are not part of the high yielding trees, some of the individuals studied have interesting characteristics for both the industry and plant breeding. These include trees G27, I11, I12 and G24 with sugar contents of 37.72, 28.82, 27.15 and 26.24 Brix, respectively. These trees offer an opportunity to diversify the purpose of cashew production in Ivory Coast, by promoting apples for beverages and numerous high added value products such as dextran, lactic acid, mannitol, oligosaccharides, bioethanol, and biosurfactants as reported by Akinwale (2000), Honorato et al. (2007), and Kannan et al. (2021). The cashew apple represents 90% of the total fruit weight (Akyereko et al. 2023), which offers a comparative advantage over nuts, in terms of volume of harvest valorized and added value (Honorato et al. 2007; Kannan et al. 2021).

Elite trees have been identified in three of the four climatic zones where cashew is produced in Ivory Coast: three (A11, A15 and A43) in the Sudanian savannahs zone, two (H23 and I25) in the sub-Sudanian savannahs zone, and six (J23, K31, L13, L33, L34 and L45) in the Guinean savannahs zone. The three high yielding trees (E22, E31, and F21) identified in humid tropical forests zone belong to the second class of performance, with 15–20 kg nuts per year. A previous study also revealed that the humid forest is not suitable for the realization of appropriate yields in cashew (Dedzoe et al. 2001). In addition, the

practice of cashew cultivation is relatively recent in the forest zone of the Ivory Coast which is rather suitable for the cultivation of several other cash crops such as cocoa, oil palm, rubber, and coffee. These cash crops which are cultivated since the colonial period on several million hectares (Chauveau and Léonard 1996) generate more income (Hashmiu et al. 2022; Yeboah et al. 2023). Consequently, farmers from tropical humid forests pay less attention to the selection of high yielding genotypes for cashew orchard creation. Pending further evaluation of these trees in the genotype - environment (GxE) interaction tests to confirm the observed performance, local dissemination of the identified trees can be carried out to improve the yield of cashew orchards in Ivory Coast. In Vietnam and Tanzania, most varieties resulting from mass selection in peasant fields are distributed locally in the form of polyclonal seeds.

The phenetic diagram resulting from the multivariate analyzes shows two groups with 44 and 77 trees. The group of 44 trees was mainly composed of individuals grown in Indenié-Djuablin whereas this with 77 trees was dominated by individuals from Bafing (36%) and Folon (44%). We noted that the 42 identified as promising trees are almost evenly distributed between the two groups. However, the distribution of trees in the two groups is irrespective of the climatic zones.

Bafing and Folon are neighboring regions inhabited by populations belonging to the same linguistic group, who maintain important trading activities, including agricultural products. Thus, high gene flows through seeds exchanges between the two regions is expected. Indenié-Djuablin region, whose trees contribute mainly to the composition of the group containing 44 trees, is very far from the other three regions (400–800 km). In this case the genetic isolation by distance can be hypothesized (Liu et al. 2023).

In a study on 36 potential high yielding trees collected in two administrative regions of the northern Ivory Coast (sub-Sudanian savannahs), and examining 14 quantitative traits, Kouakou et al. (2018) observed three groups of 12, 14 and 10 trees. Another study on 221 trees examined using 18 SSR markers revealed only two genetic groups (Kouakou et al. 2020). Thus, the present study and these of Kouakou et al. (2018, 2020) show that despite the significant variability observed, genetic differentiation in cashew orchards in Ivory Coast is relatively low. This result can be explained by the relatively recent introduction of cashew in the country, from accessions of undiversified origins and narrow genetic basis, namely few seed samples. Indeed, the first cashew stands were carried out from 1929 to 1969 by the Ivorian office of Waters and Forest on thousands of hectares using nuts of unknown origin (Bassett 2017). Subsequently, the Society for the Development of Fruit and Vegetable Production (SODEFEL) imported seeds of the variety Jumbo from Brazil, to create a seed orchard in Badikaha (northern Ivory Coast). To face peasant growing demands in seeds due to greater international interest for cashew nuts, the National Centre of Agricultural Research (CNRA) installed a seed orchard of 200 trees from nuts of variety Jumbo and some accessions from Benin and Australia at the research station of Lataha (North Ivory Coast). Since the 1990s, CNRA distributes annually 200–300 kg of polyclonal seeds to Ivorian cashew farmers so that 1.4 million hectares are installed today using just few genetic resources.

The promising trees identified here can undergo genotypic characterization and be transferred to the national germplasm for further observations in various environments to enhance the reliability of the comparisons. Gametophytic compatibility and the analysis of genotype-environment interactions of the selected trees are also necessary for a better evaluation. The use of highly discriminant genetic markers (i.e., SNP) could highlight the fine genetic structure of trees present in cashew orchards in Ivory Coast, with reference to performance and geographical origin. Such analyses are useful to guide future breeding program, collection works, characterization, and prospects.

Declarations

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Author contributions

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Figures

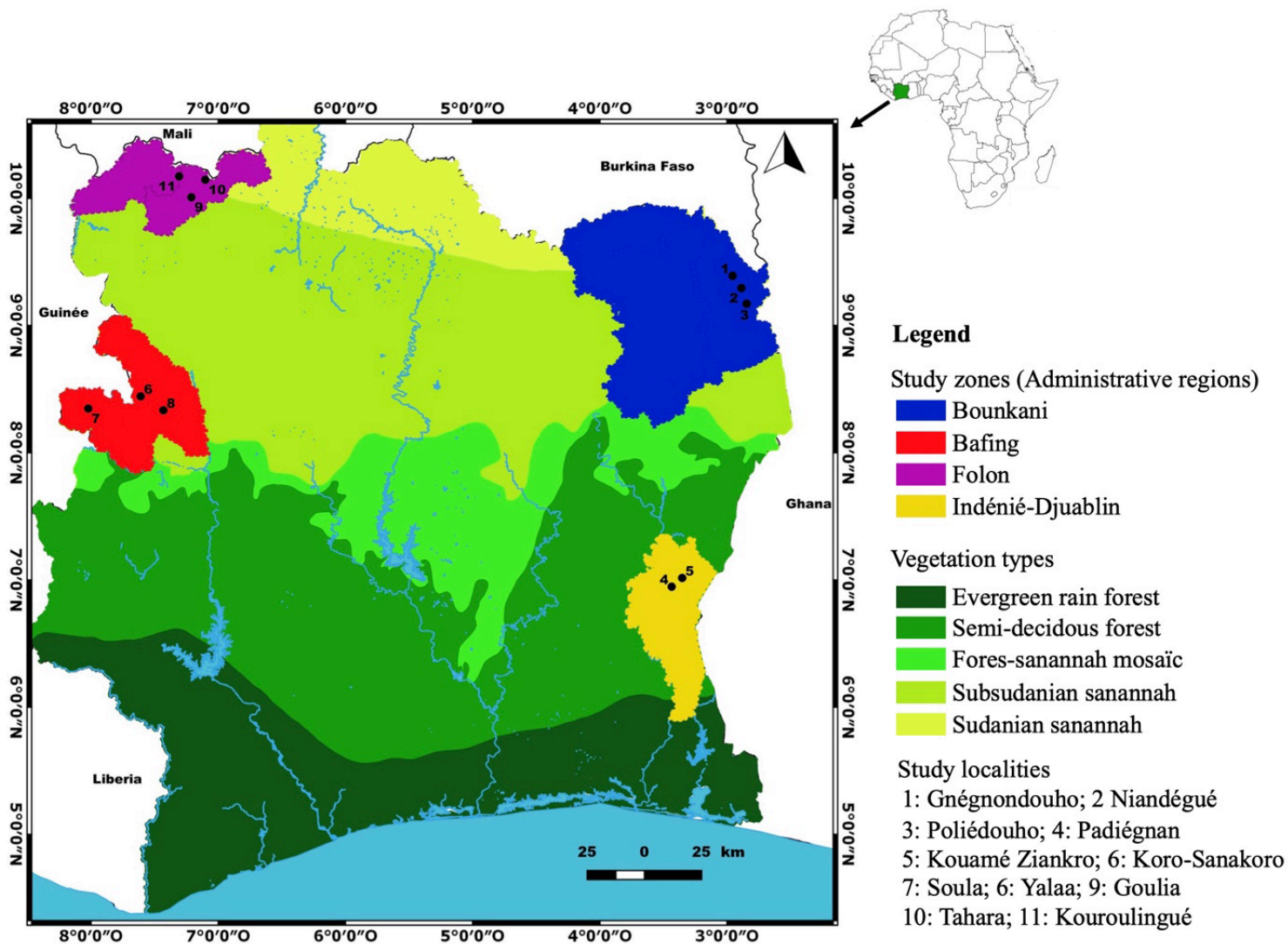


Figure 1

Participatory characterization zones of cashew trees and vegetation types in Ivory Coast. The dots and numbers in the sampled regions indicate the sampled localities and the number of sampled trees



Figure 2

Phenetic diversity in fruits and nuts of cashew trees: clusters of low (a) and high (b) fruit load; smallest (c) and biggest (d) fruits; nuts of the lowest (e) and highest weight

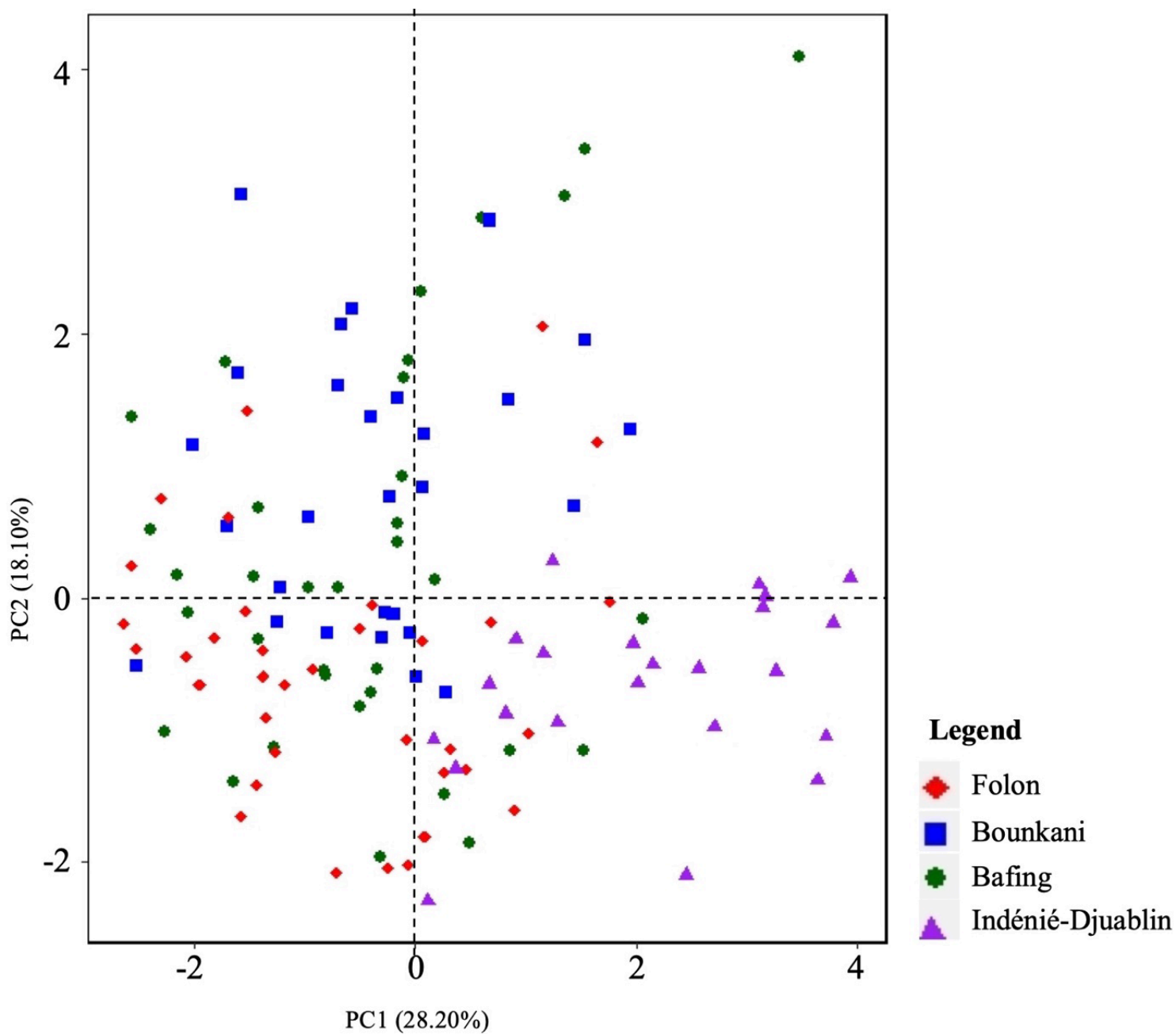


Figure 3

Projection of 121 cashew trees in plane 1-2 of Principal Components Analysis (PCA)

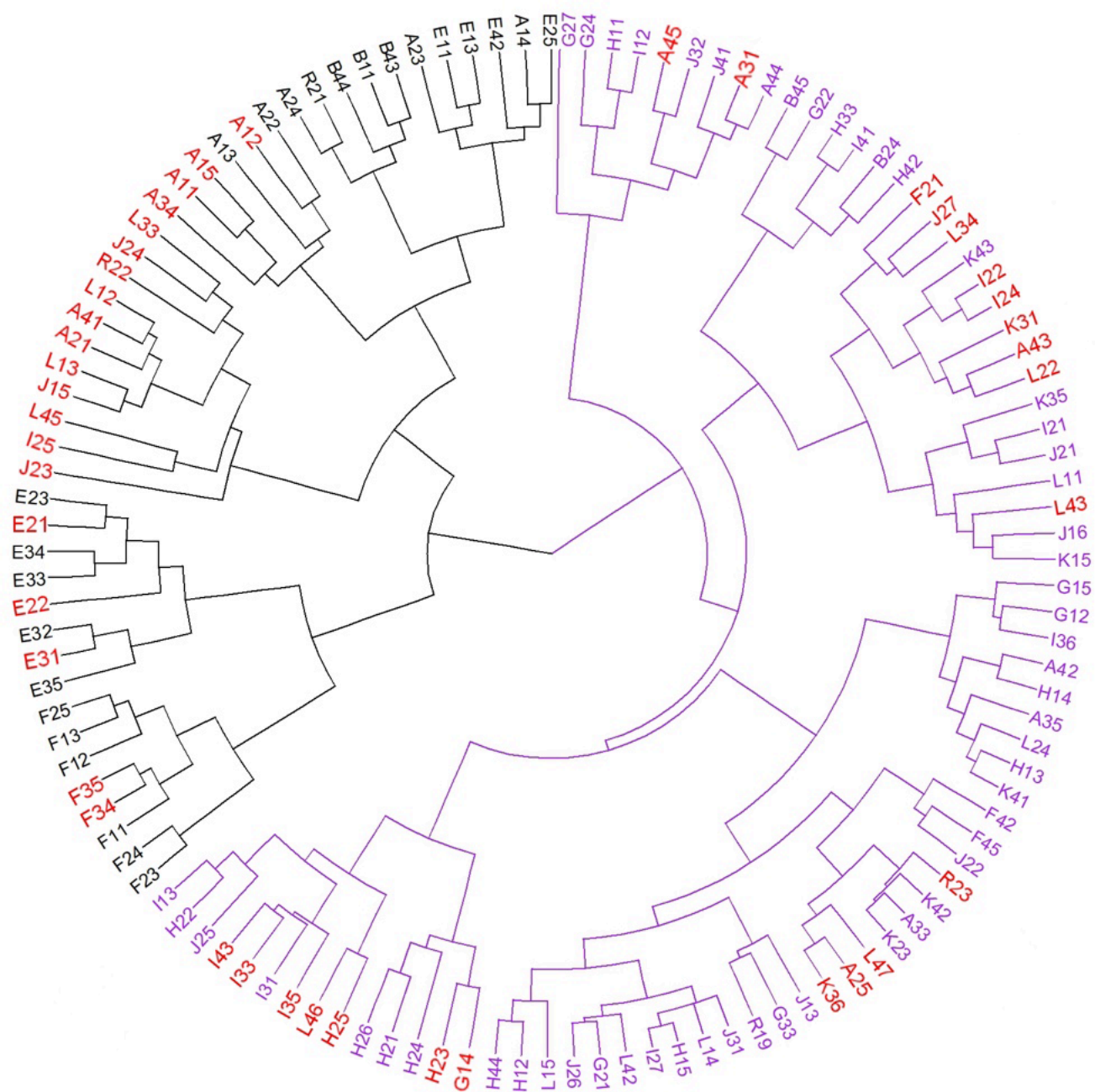


Figure 4

Ward's method based phenetic tree of the 121 cashew trees. Tree branches are color-marked according to groups (Group 1 in black and Group 2 in mauve). Red color identifies codes of promising cashew trees