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Research Article

Characterization of the flowering and fruiting phenophases of 21 cashew (*Anacardium occidentale* L.) genotypes from Côte d'Ivoire

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Abstract

Cashew (*Anacardium occidentale* L., Anacardiaceae) is an important cash crop with high economic and nutritional value. Yet nut production in cashew orchards remains low throughout the Côte d'Ivoire. Here, we update current knowledge of cashew flowering and fruiting phenophases in order to optimise production in the country's orchards. The modified three-digit scale of Biologische Bundesantalt, Bundessortenamt and Chemische Industrie (BBCH), was used to describe growth stages in detail on twenty-one cashew genotypes from the Badikaha cashew orchard. Four main growth stages (two floral and two fruiting) were determined. In terms of floral phenology, three secondary growth stages were identified and described, namely two inflorescence development stages (510 and 513) and a flowering stage (616). As a result, 15 secondary stages of flowering cashews were described. A secondary stage of nut and apple development (714) was also identified, bringing to 11 the number of secondary stages of fruiting phenology currently described in cashew. The different growth stages (inflorescence emergence, flowering, fruit development and fruit maturity) of cashew genotypes in Côte d'Ivoire were described in detail, providing new tools for improving cashew cultivation practices and hybridisation by breeders.

1. Introduction

Cashew (*Anacardium occidentale* L., Anacardiaceae) is a tree species that is native to Brazil [1]. Cashew was first introduced to Côte d'Ivoire in 1951 to reforest cutover lands, and mitigate soil erosion [2]. Between 1959 and 1960, cashew forest plantation programs were implemented by seeding nuts in the northern and central parts of Côte d'Ivoire and, subsequently, throughout the entire Sudano-Guinean savanna zone [2]. Since 2015, Côte d'Ivoire has become the world's largest producer of cashew nuts, producing 700,000 tons in 2015 [3]. Production exceeded more than one million tons in 2022 [4].

MINADER showed approximately 330,000 households (about 1.9 million people) would be involved in cashew production, making it the most important source of income in rural areas in the northern part of the country [5]. This crop contributes to the acquisition of goods and services by producers in Côte d'Ivoire. For instance, [6] showed that at the end of each season, cashew marketing improved annual net income per hectare by 78–80% of the average annual income received by households in Côte d'Ivoire.

However, the low diffusion of improved planting

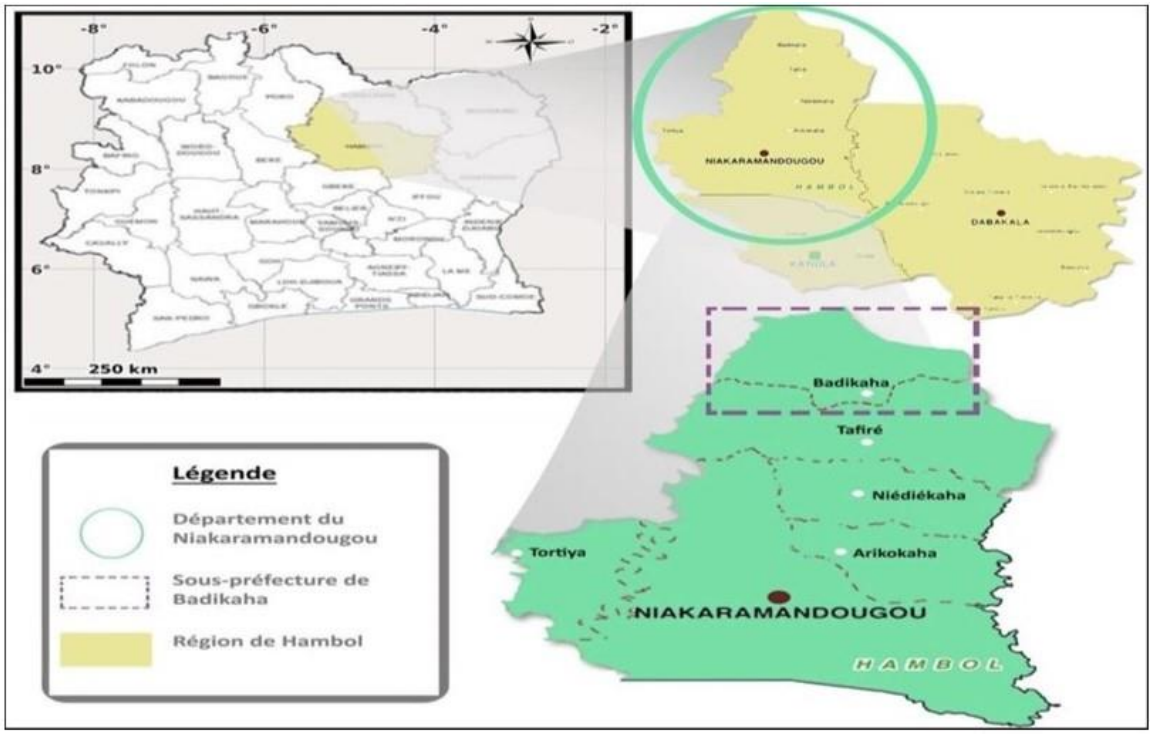

Figure 1. Location of the study area

materiel, the strong pressure from pests and a lack of adoption, combined these issues result in relatively low nut yields (524 kg ha^{-1} on average) compared to the minimum of 1,000 kg ha^{-1} harvested from orchards in India and Brazil. Thus, it is important todelineate the phenological growthstages of the cashew trees in Côte d'Ivoire. For instance, [7] stated that mastering the phenology of crop species improves the effectiveness and efficiency of crop management practices, varietal improvement programs, and germplasm characterization.

The proper understanding of cashew phenological growth stages may contribute to more efficient planning of management practices of this important crop, to optimize production in Côte d'Ivoire. In this context, this study aimed to describe the complete floral and fruit development stages in cashew according to the BBCH scale.

2. Materials and methods

2.1 Plant material

Plant material included 21 grafted cashew genotypes. These genotypes were selected based on the nut yield of their mother trees and on the basis of their high kernel content (Table 1). The study area coincided with the sub- prefecture of Badikaha (Hambol region), which is located in the north- central region of Côte d'Ivoire. The experimental site was located 6 km from the town (9° 12' north; 5° 10' west; Fig. 1). The climate of this region is tropical, and is characterized by two alternating seasons: a rainy season from May to September, and a dry season from October to April. The average annual temperature is 25.9 °C. The average annual rainfall is 1130 mm, in 2021. The soil of the region is ferralitic type, which is predominantly clayey- sandy and gravelly [19]. The vegetation is dominated by clear forest (wooded savanna) and wooded savanna [16].

2.2 Methods

A 1.5 ha orchard in Badikaha was established on September 15, 2016. The site had a systematic, non-classical setup consisted of two blocks. The first block was complete with 21 genotypes. The second block was incomplete, and had 13 genotypes. The first block contained 336 plants (16 trees x 21). Each row had one genotype with 16 trees. A distance of 5 m was maintained between trees and genotypes. Five trees were observed (candidate trees) per genotype (Fig. 2). Trees were selected based on the high number of shoots at stage 319 of the extended BBCH scale created by [8].This stage represents the reference stage for the current study (Table 2). It is characterized by well-matured shoots (fully developed dark green, leathery leaves). One-hundred and five trees were selected.

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Table 1. Origin and characteristics of the mother trees of the 21 cashew genotypes used in the present study

Regions / Localities	Genotypes	Origin	Yields (kg/tree)		Percentage Kernel Out-turn (%)		Age of trees in 2016 (year)
			2015	2016	2015	2016	
Hambol / Badikaha (Tafiré) pour Katiola	KADM-98	Karakoro	34	39	27	22.9	16
	KADM-105		26.5	23	28.9	30.1	13
	KADM-181		20	9	32	25.5	16
	KADM-103		45	21.6	27.3	24.5	16
	KADM-96		-	15	25.8	25.0	16
	KADM-100	Koni	27	14.7	28.1	31.8	16
	KADM-84		48.5	32	42	26	25
	KADM-85		17.5	19	27.6	27.9	25
	KADM-112		10	39	28.6	27.2	18
	KADM-37	Boundiali	21.5	14	28.1	25.1	19
	KADM-106		-	11	29.2	29.2	18
	KADM-35		25.3	14.4	30	23.6	19
	KADM-87	Sinématiali	-	60.8	-	27.6	19
	KADM-90		-	28.7	-	27.1	19
	KADM-91		-	29	-	27	19
	KADM-76	Waraniéné	12.5	10.5	26.5	26.8	11
	KADM-195	Fronan	-	20	-	25.3	19
	KADM-189	Katiola	-	7,5	-	27.9	8
	LAX3264	Lataha	-	18[a]	-	27.09	31
	LAX4297		-	19[a]	-	28.04	31
	LAZ330		-	13[a]	-	28.53	31

a: Average yield (1994-2002) in kg of nuts/tree/year.

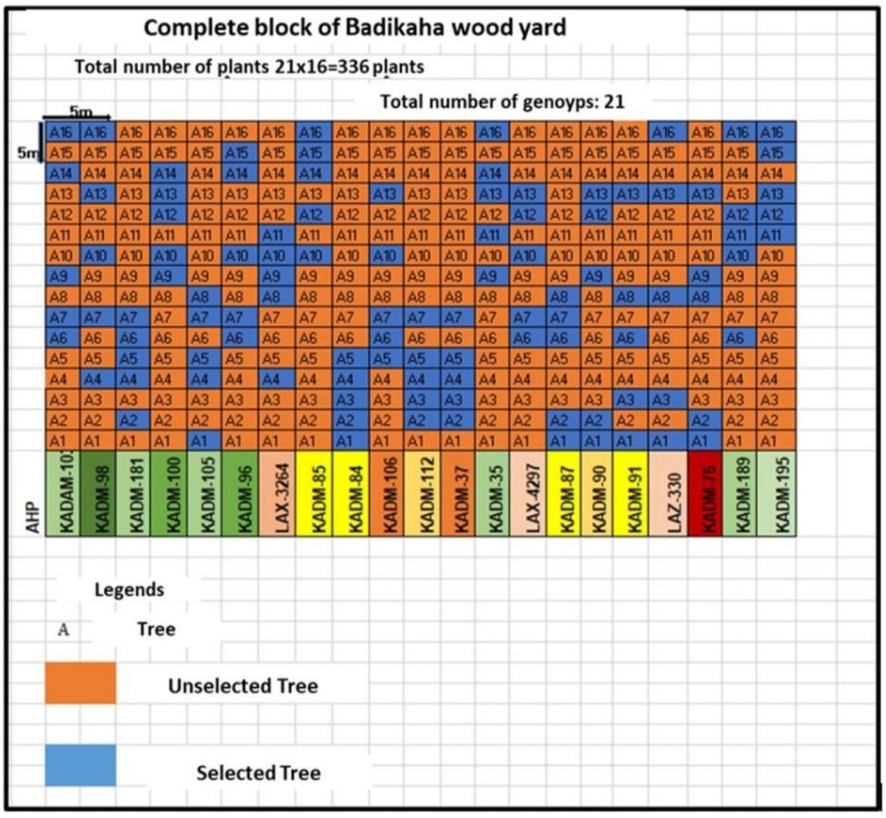

Figure 2. Experimental device

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Table 2. Description of growth stage 3: shoot development.

Phenological stage code	Secondary stages	Description	Illustration
319	Vegetative growth stage: development of leafy shoots. (initial stage of the study).	Fully mature shoots, fully developed leaves, dark green color, leathery.	

Two twigs were then tagged in each cardinal direction on each candidate tree. Eight-hundred andforty twigs were labeled on the 105 selected trees. After tagging, twig evolution was monitored using the three-digit extended BBCH scale of [8]. Shoot development was observed daily from labeling to the end of flowering. After flowering, fruiting was observed every three days per week until ripening.

Data were collected on the floral, fruiting, and yield traits of the 21 cashew genotypes. All data were collected over six months, from October 5, 2020, to April 5, 2021. The identified phenological growth stages were photographed with the digital camera (Nikon Coolpix W100).

3. Results and discussion

3.1 Variation in phenological stage

This study identified four major and 26 minor growth stages for cashews. The main flower growth stages were: two floral phenophase stages (inflorescence and flowering stage). These two main stages were formed of 15 secondary stages. Out of the 15 secondary stages offloral phenology, three secondary stages had not been previously recorded by [8]. These included two secondary stages within the main inflorescence stage (stages 510 and 513),and one secondary stage in the main flowering stage (stage 616). At the fruit level, two fruiting phenophase stages (fruit development and ripening stage), encompassing 11 secondary stages, were recorded. The secondary stage 714 that has been described in the current study was not observed by [8]. Thus, four secondary stages (510, 513, 616,and 714) of floral and fruiting phenophases were found in this current study.

Vegetative: For the 21 genotypes, bud break (i.e., end of vegetative growth stage and beginning of inflorescence stage) occurred at 6 weeks (from November 10, 2020) to 9 weeks (Table 3). It lasted 6 weeks in early flowering genotypes (KADM-103 and KADM- 195), 8 weeks in intermediate flowering KADM-100, KADM-35, LAX-3264, KADM-181, KADM-98, KADM-76, KADM-90, and KADM-96), and 9 weeks in late flowering genotypes (KADM-112, KADM-85, and LAX-4297).

Flowering: Intermediate and late flowering genotypes initiated reproductive buds (inflorescence stage) 2 weeks and 3 weeks after the early flowering genotypes, respectively (Table 3). For all three types of flowering genotypes, the transition from early flowering to 100% flowering spanned 5 weeks.

Fructification: The fruit development stage started 13, 15, and 16 weeks after bud break for early, intermediate, and late flowering genotypes (Table 3), respectively. For all three types, the transition from early fruiting to 100% fruiting spanned 3 weeks. There was a 7-week period between flowering and fruiting, regardless of genotype. Budbreak to 100% fruiting required 16, 18, and 19 weeks for early, intermediate, and late flowering genotypes, respectively.

Our study is in agreement with other studies using, in the last three decades, the extended Biologische Bundesantalt, Bundessortenamt and Chemische Industrie (BBCH) scale to describe the phenological stages [10] of several annual and perennial crops. Examples of crops include grapevine [12], citrus [13], guava [14], cocoa [11], mango [15], and cashew [8].

3.2 Flower development stages

Two stages of floral phenology were determined for

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Table 3. Flowering and fruiting period of 21 cashew genotypes (S = weeks)

	Flowering				Fructification			
Genotype	**Stage 319**	**Beginning**	**50%**	**100%**	**Beginning**	**50%**	**100%**	**Fl period**
KADM-103	S0	S6	S9	S11	S13	S15	S16	Precocious
KADM-195	S0	S6	S9	S11	S13	S15	S16	Precocious
KADM-98	S0	S8	S11	S13	S15	S17	S18	intermediate
KADM-181	S0	S8	S11	S13	S15	S17	S18	intermediate
KADM-100	S0	S8	S11	S13	S15	S17	S18	intermediate
KADM-105	S0	S8	S11	S13	S15	S17	S18	intermediate
KADM-96	S0	S8	S11	S13	S15	S17	S18	intermediate
Lax-3264	S0	S8	S11	S13	S15	S17	S18	intermediate
KADM-84	S0	S8	S11	S13	S15	S17	S18	intermediate
KADM-106	S0	S8	S11	S13	S15	S17	S18	intermediate
KADM-37	S0	S8	S11	S13	S15	S17	S18	intermediate
KADM-35	S0	S8	S11	S13	S15	S17	S18	intermediate
KADM-87	S0	S8	S11	S13	S15	S17	S18	intermediate
KADM-90	S0	S8	S11	S13	S15	S17	S18	intermediate
KADM-91	S0	S8	S11	S13	S15	S17	S18	intermediate
Laz-330	S0	S8	S11	S13	S15	S17	S18	intermediate
KADM-76	S0	S8	S11	S13	S15	S17	S18	intermediate
KADM-189	S0	S8	S11	S13	S15	S17	S18	intermediate
KADM -85	S0	S9	S12	S14	S16	S18	S19	belated
KADM-112	S0	S9	S12	S14	S16	S18	S19	belated
LAX-4297	S0	S9	S12	S14	S16	S18	S19	belated

cashew: the inflorescence stage and the flowering stage (Table 4).

Inflorescence stage (stage 5): Eight secondary stages describing the inflorescence stage were delineated (Table 4). These are: 510; 511; 513; 514; 515; 516; 517 and 519. The inflorescence stage begins with secondary stage 510, which follows stage 319. Stage 510 is characterized by the initiation of the reproductive bud, marking the start of the swelling of the reproductive bud. Stage 513 then occurs at the start of panicle elongation. Stages 513, 514 and 515 are marked respectively by the development of floral buds passing through 3, 4 and 5 floral buds on the panicles during panicle development. Stages 516 and 517 represent the development of panicular branches. Stage 519 marks the end of panicle development, with a network of swollen flower buds on the panicle branches.

Flowering stage (Stage 6): Seven secondary stages (Table 4) were recorded (610; 611; 613; 615; 616 and 617). The flowering stage begins with the opening of the first flower bud (stage 610), formed during the inflorescence stage, and ends at stage 619 (end of flowering and appearance of the first fruit set). The secondary stage 611 corresponds to 10% of flowers open (i.e. 10/100 flower buds open). The opening of 30 % of flowers indicates secondary stage 613 (i.e. 30/100 flowers are open). Secondary stages 615 and 616, marked respectively by the opening of 50 and 60% (i.e. 50/100 and 60/100) of flowers. The 617 stage is characterized by the opening of 70% (i.e. 70/100) of the flowers and finally the 619 secondary stage with 90 to 100% (i.e. 90/100 to 100/100) of the flowers open.

3.2 Fruiting phenophases

Two stages of fruiting phenology were determined for cashews: the fruit development stage and the fruit ripening stage (Table 5). Fruit development stage (stage 7): This stage is composed of six sub-stages delimiting the development of the fruit (Table 5). These sub-stages are: 711, 713, 714, 715, 717 and 719. The fruit development stage begins with sub- stage 711, in which the nut is soft and represents about 10% of the final size (i.e. 10/100), and the apple represents about 2.5% of the final size (i.e. 2.5/100).The surface colour of the nut and apple was green. Stage 713 occurred later, with the nut at 30% of the final size (i.e. 30/100)

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Table 4. Description of floral phenophases of 21 cashew genotypes

Inflorescence stage (Stage 5)			
Phenological stage code	**Secondary stage**	**Description**	**Illustration**
510	Appearance of a new shoot (8 days after fully mature leaves 319). Stage 510 is the initiation stage of the reproductive bud and is located between stages 319 and 511.	This new shoot: the reproductive bud.	
511	Beginning of reproductive bud swelling (11 days after stage 510).	Visible inflorescence bud.	
513	Beginning of panicle elongation (9 days after stage 511).	Appearance of three flower buds.	
514	Panicle elongation (8 days after stage 513).	Beginning of separation of the laterals, with four or five floral buds visible.	
515	Lateral elongation continues (also 8 days after stage 514).	Separation of laterals continues with the presence of five to six flower buds.	

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Table 4. *(Continued)*

Inflorescence stage (Stage 5)			
Phenological stage code	**Secondary stage**	**Description**	**Illustration**
516	Beginning of appearance of the sub-laterals from the main laterals (8 days after the 515 stage).	Average presence of 19 flower buds is observed.	
517	No more separate and elongated sub-laterals (14 days after stage 516).	An average of 38 flower buds is observed.	
519	End of main and lateral Panicle development (8 days after stage 517).	With an average of 48 swollen flower buds.	
Flowering stage (Stage 6)			
610	Beginning of flowering (4 days' after stage 519).	Opening ofthe first flower bud.	
611	Floweringat 10% (8 days after 610).	10/100 flowers opened.	

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Table 4. *(Continued)*

Flowering stage (Stage 6)			
Phenological stage code	**Secondary stage**	**Description**	**Illustration**
613	Floweringat 30% (8 days after stage 611).	30/100 of flowers opened.	
615	50% flowering (8 days after the 613 stage).	Half of the flowers opened (estimated 50/100 open flower buds).	
616	Flowering at 60% (10 days after stage 615). Stage 616 is a secondary sub-stage between 615 and 617.	60/100 of flowers are open in the panicle.	
617	70% flowering (13 days after stage 616).	Early opened flowers are dried (70/100 of flowers opened).	
619	90% to 100% flowering (8 days after stage 617).	End of flowering (90/100 or 100/100 of flower buds are open), and appearance of the first fruit set.	

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Table 5. Description of fruiting phenophases in 21 cashew genotypes.

Fruit development stage (Stage 7)			
Phenological stage codes	**Secondary stage**	**Description**	**Illustration**
711	Fruit at 10% of final size (7 days after stage 619). Nut is at 10% of its final size.	Nut is 10/100 and the apple is 2.5/100 of final size.	
713	Fruit at 30% of final size (9 days after stage 711).The nut is at 30% of its final size.	Nut has a size of 30/100 and the apple is 5/100 of their final size. Pink hues visibleon the surface ofthe fruit (nut and apple).	
714	Fruit at 40% of final size (9 days after stage 713).	Nut is 40/100 and the apple is 6/100 of final size. The fruit has a marked pink coloration and longitudinal ridges are beginning to appear on the surface of the apple.	
715	Fruit at 50% of final size (9 days after stage 714).	Nut reaches half of its final growth 50/100 and the apple is 7.5/100 of its final size, with more visible longitudinal ridges on the surface of the apple.	
717	Fruit at 70% of final size (9 days after stage 715).	Nut has reached 70/100 and the apple is 10/100 of final size, and longitudinal ridges continue to appear.	

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Table 5. *(Continued)*

Fruit development stage (Stage 7)			
Phenological stage codes	**Secondary stage**	**Description**	**Illustration**
719	Fruit at 90% of final size (9 days after stage 717).	End of the growth of the nut, at 90/100 of the final size; apple is 15/100 of final size; longitudinal ridges become prominent.	
Fruit ripening stage (Stage 8)			
813	Beginning of fruit maturity (9days after stage 811).	Whole nut turns greenish gray; nut hardens; surface of the apple is light green, and is 30/100 of final size.	
815	Advanced fruit maturity (9 days after stage 813).	Nut turns whitish apple surface becomes yellowish, and reaches about 50/100 of final size.	
817	Post-advanced fruit maturity (7days after stage 815).	Nut turns to ash color; orange or red color begin to appear on the yellowish surface of the apple; apple.	
319	Horticultural fruit maturity (7 days after stage 817).	Reaches about 70/100 of final size. Nut and apple are completely ripe; apple reaches about 90/100 of final size; color of apple surface depends on genotype (yellow/red/orange).	

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and the apple at 5% of final size (i.e. 5/100). The surface colour of the nutand apple was pink. Stage 714 Stages 715, 717 and 719 represent successive stages of development, with the nut reaching 40% of its final size. Stage 714 was missed in the study conducted by Adiga and colleagues [8]. This stage was highlighted in the present study, bringing to 11 the number of secondary stages of the fruiting phenophase described in the cashew tree. Stages 715,717 and 719 represent successive stages of development, with the nut reaching 50%, 70% and 90% of its final size (i.e. 50/100, 70/100 and 90/100) and the apple reaching 7.5%, 10% and 15% of its finalsize (i.e. 7.5/100, 10/100 and 15/100). At these secondary stages (stages 715, 717 and 719), the nuts have become greener,with a visible ridge on the surface of the apple. Stage 719 represents the end of total cashew nut growth (physiological maturity of the nut), while the apple has continued to grow during the ripening phase.

Fruit ripening stage (stage 8): Five secondary stages of ripening was delineated (Table 5). These secondary stages are: 811, 813, 815, 817 and 819. The ripening stage begins at secondary stage 811, when the apple has reached about 20% of its final size (i.e. 20/100). The surface of the apple was light green, and the shell of the nut became dark green, with grey on its surface.

At stage 813, the apple had reached around 30% of its final size (or 30/100). The surface of the apple remained light green, while the whole nut turned greenish grey and continued to harden. At stage 815, the apple has reached about 50% of its final size (50/100). The surface of the apple has taken on a yellowish colour and the nut has turned whitish grey. At stage 817, the apple hasreached about 70% of its final size (70/100). The surface of the apple has begun to show shades of orange or red on the yellowish surface, while the nut has taken on an ashen colour. Stage 819 represents the end of the fruit's ripening phase. At this stage, the nut and apple were completely ripe (horticultural maturity of the fruit). The apple was at 90-100% (i.e. 90/100 or 100/100) of its final size.

3.3 Duration of secondary stages for floral and fruiting phenophases

In total, 26 flower and fruit phenophase substages were recorded in the 21 cashew genotypes (Table 6). The duration of the eight substages from the inflorescence stage was 74 days, on average. For the flowering stage, theseven secondary stages averaged 59 days. The six secondary stages of fruit development averaged 52 days. The fruit ripening stage lasted just 36 days, and had five secondary stages. The floral phenophases were the longest stages, with 15 secondary stages spanning 133 days, on average. Fruit phenology (with 11 secondary stages)

Table 6. Floral and fruiting phenophases secondary stages duration

Main stage	Secondary stage	Duration of secondary stage
	Stages 319 to 510	8 days
	Stages 510 to 511	8 days
	Stages 511 to 513	11 days
	Stages 513 to 514	9 days
	Stages 514 to 515	8 days
	Stages 515 to 516	8 days
	Stages 516 to 517	8 days
	Stages 517 to 519	14 days
Stage of the inflorescence	Total duration	74 days, Approximately 2.5 months
	Stages 519 to 610	4 days
	Stages 610 to 611	8 days
	Stages 611 to 613	8 days
	Stages 613 to 615	8 days
	Stages 615 to 616	10 days
	Stages 616 to 617	13 days
	Stages 617 to 619	8 days
Flowering stage	Total duration	59 days, Approximately 2 months
	Stages 619 to 711	7 days
	Stages 711 to 713	9 days
	Stages 713 to 714	9 days
	Stages 714 to 715	9 days
	Stages 715 to 717	9 days
	Stages 717 to 719	9 days
Stage of fruit development	Total duration	59 days, Approximately 2 months
	Stages 719 to 811	4 days
	Stages 811 to 813	9 days
	Stages 813 to 815	9 days
	Stages 815 to 817	7 days
Fruit ripening stage	Stages 817 to 819	7 days
	Total duration	36 days, Approximately 1 month

Total of days in the main stages: 221 days, about 7.5 months

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lasted 88 days. Overall, the 26 secondary stages of the floral and fruiting phenophases lasted 221 days, on average. In the present study, the floral and fruiting phenophases lasted 133 and 88 days, respectively. These results supported those of [17], who showed that the anthesis of cashew flowers lasted about 150 days. Masawe et al. recorded inflorescences at different stages on the same tree, and even on the same inflorescence (flower buds, open flowers, fruit set, immature fruit, and mature fruit) [18]. This phenomenon is used to determine the type of maturity ofcashew fruit (i.e., grouped, intermediate, or spread out). That could be one of the reasons that would explain the poor performance of cashew planting material used in Côte d'Ivoire. In the mango tree for example, the production cycle of the Cogshall variety of mango grown on St. Pierre (Reunion) lasts 1.5 years. This cycle is separated into four important periods (or phenological stages): vegetative growth, vegetative rest, flowering, and fruiting [9].

4. Conclusions

This study identified four main growth stages and 26 secondary growth stages in 21 cashew genotypes grown in a wool field at Badikaha, Côte d'Ivoire, using the extended BBCH scale definedby. Of these 26 secondary stages, 15 and 11 were flower and fruit phenophases, respectively. The present study identified four previously undescribed secondary stages incashew; three secondary stages, including two of inflorescence (secondary stages 510 and 513), and oneof flowering (secondary stage 616). Another secondary stage of the fruiting phenophase was also identified (secondary stage 714). The description of the different phenological stages of the 21 cashew genotypes in this study provided tools for developing technical approaches to optimize production and creating new varieties through controlled hybridization.

Authors' contributions

Conception, original idea, data collection, writing, analysis and statistical processing of data, C.K.K.; Drafting, correction and revision of the manuscript, F.L.; Research orientations and manuscript revision, A.K.J.; Guidelines, research orientations, drafting of the manuscript and review of previous versions of this article, C.K.K.

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Availability of data and materials

All data will be made available on request according to the journal policy.

Conflicts of interest

The authors declare no conflict of interest.

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