Journal of Zhejiang University-SCIENCE B (Biomedicine & Biotechnology)
ISSN 1673-1581 (Print); ISSN 1862-1783 (Online)
www.zju.edu.cn/jzus; www.springerlink.com
E-mail: jzus@zju.edu.cn

Effect of physiological harvest stages on the composition of bioactive compounds in Cavendish bananas*

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Received June 26, 2012; Revision accepted Jan. 11, 2013; Crosschecked Mar. 7, 2013

Abstract: The combined influence of maturation, ripening, and climate on the profile of bioactive compounds was studied in banana (*Musa acuminata*, AAA, Cavendish, cv. Grande Naine). Their bioactive compounds were determined by the Folin-Ciocalteu assay and high-performance thin layer chromatographic (HPTLC) method. The polyphenol content of bananas harvested after 400 degree days remained unchanged during ripening, while bananas harvested after 600 and 900 degree days exhibited a significant polyphenol increase. Although dopamine was the polyphenol with the highest concentration in banana peels during the green developmental stage and ripening, its kinetics differed from the total polyphenol profile. Our results showed that this matrix of choice (maturation, ripening, and climate) may allow selection of the banana (*M. acuminata*, AAA, Cavendish, cv. Grande Naine) status that will produce optimal concentrations of identified compounds with human health relevance.

Key words: Banana, Ripening, Harvest ages, Polyphenol, Dopamine, Starch
doi:10.1631/jzus.B1200177 **Document code:** A **CLC number:** S668.1; Q945.1

1 Introduction

The banana is now produced in about 120 countries on the five continents, and is among the most cultivated of all fruits (Lassoudière, 2007). About 85% of banana production is used for local consumption or industrial purposes, and only 15% is exported (Lescot, 2006). In the French West Indies (FWI), the banana (*Musa acuminata*, AAA, Cavendish, cv. Grande Naine) is almost the sole cultivar and unfortunately is often grown as an intensive monoculture. Despite its contribution to local economic activities and high production of up to 500000 t/a, the banana faces global competition, environmental and, more importantly, industrial processing issues. The quality screening for the industrial processing of banana requires knowledge of several parameters such as the cultivar, development stage, and postharvest characterization. Health awareness combined with novel functionality has increased the demand for banana-based products with good health benefits. The most abundant compounds in bananas such as carbohydrates, including starch, and soluble sugars have been studied, but few studies have focused on the kinetic accumulation of bioactive compounds.

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* Project supported by the French Region Country Government of Guadeloupe using the long term fellowships provided with the European Social Fund 2007-2013

Reports of the chemical composition of the banana have shown that it is rich in minerals and dietary fiber, and is a good source of vitamins C and E (von Loesecke, 1950). Similarly, the antioxidants gallocatechin, catechin, and epicatechin were previously identified in banana (Someya *et al.*, 2002). However, the maturation stage and the postharvest treatments were not specified in the study. Despite the status of the banana as a climacteric fruit, the distribution of bioactive and nutritional compounds was poorly described as a function of major parameters. Here, the influence of maturation and ripening on the profile of bioactive compounds in banana (*M. acuminata*, AAA, Cavendish, cv. Grande Naine) was studied at the green developmental stages of 400, 600, and 900 degree days (dd). The general features and chemical composition of the bananas were assessed. We showed that pre-harvest factors (climate and maturation) affected fruit weight, starch and polyphenols/dopamine levels with an inverse correlation between maturity and compound concentrations. Also, dry periods and immaturity differentially increased the total content of polyphenols compared to the dopamine content. The postharvest factor (ripening) impacted the chemical evolution profile depending on the development stage.

This work may contribute to the FWI banana brand by validating nutritional data about the content of some bioactive compounds. Indeed, such data provide a more complete description of the organoleptic and chemical properties of FWI bananas (*M. acuminata*, AAA, Cavendish, cv. Grande Naine).

2 Materials and methods

2.1 Materials

The banana fruits (*M. acuminata*, AAA, Cavendish, cv. Grande Naine) used in this study were harvested in October 2010, during the hot humid season (wet period, WP) and in May 2011, during the cool dry season (dry period, DP) as previously described (Bugaud *et al.*, 2007). All bananas were grown in the same soil zone and obtained from the CIRAD, Neufchâteau Station, at Sainte Marie, Capesterre-Belle-Eau, in Guadeloupe, France.

All tissues used in this study were harvested from six banana plants (*M. acuminata*, AAA, Cavendish, cv. Grande Naine) grown at the CIRAD research station (elevation: 250 m; andosol; rainfall: 3500 mm/a), Guadeloupe. During growth, fruit bunches on banana plants were covered with blue plastic bags to hamper insect infestations, and to streamline the development of whole fruits on the bunch. Based on the heat unit concept (Ganry and Meyer, 1975; Jullien *et al.*, 2008), green fruits were harvested at three developmental stages, namely 400 (immature green or *i*MG-fruit), 600 (early mature green or *e*MG-fruit), and 900 dd (late mature green or *l*MG-fruit) corresponding to about 40, 60, and 90 d, respectively, after flowering (Mbéguié-A-Mbéguié *et al.*, 2007). At each harvesting time, only internal fingers of the median hand on the bunch, considered as comparable (Liu, 1976), were taken into account for each bunch. After harvest and an antifungal bath, all fruits were kept for 24 h at 20 °C in chambers ventilated with humidified air before being treated with 1000 or 10000 μl/L of acetylene for 24 h at 20 °C and ambient humidity. From 1 to 9 d after treatment (DAT), a sample of three fruits was taken daily and subjected to physico-chemical analyses including color, peel hardness, pulp firmness, and dry matter (DM) measurement.

Peel tissue, without the apex and stalk, and pulp tissue were frozen separately in liquid nitrogen. Then, one part of the sample was stored at −80 °C for total phenol compound and dopamine analyses and the other part was freeze-dried for starch and soluble sugar analyses.

2.2 Color, peel hardness, pulp firmness, weight, pulp/peel ratio, and dry matter measurement

The colorimetric coordinates of fresh banana peels were measured using a Minolta Chroma Meter CR 400 (color space CIE L*, a* and b*). The rheological characteristics such as pulp firmness and peel hardness were measured on fresh bananas using a TA-XT2 penetrometer. A cylindrical metal borer with a diameter of 4.9 mm penetrated the fresh unpeeled fruit at constant speed (2 mm/s) to a depth of 10 mm. The maximum force applied to break up the peel represented the peel hardness (expressed in Newton (N)). The slope of the force/time curve represented the fruit firmness (expressed in N/s) as described by Breene (1975). For DM measurement, 2-g fresh FWI Cavendish banana was oven-dried at 105 °C for 18 h and then weighed.

2.3 Starch content measurement

Percentage fruit starch content was determined by differential scanning calorimetry (DSC) (Sievert and Holm, 1993; Mestres *et al.*, 1996). For this study, 9 mg of freeze-dried pulp powder was extracted with 40 µl of water purified through a Millipore purification system.

2.4 Determination of soluble sugars

The soluble sugars were extracted from a matrix consisting of 1 g of freeze-dried banana pulp powder in 80% ethyl alcohol at 60 °C, using an accelerated solvent extractor (ASE 200, Dionex Corp., Sunnyvale, USA). This extraction process was carried out at 100 bar (1 bar=0.1 MPa) pressure, thereby allowing the use of small amount of solvents (20–30 ml). The soluble sugar extraction lasted 15 min and was the first step in the quantification of soluble sugars by high-performance liquid chromatography (HPLC).

Five cycles were run with a static time of 7 min and a 100% flush. The extracts were diluted, filtered at 0.45 µm and injected into an HPLC DX600 (Dionex Corp., Sunnyvale, USA) with a Carbopac MA-1 column. The eluant used was sodium hydroxide of 600 or 800 mmol/L at a flow rate of 0.4 ml/min.

The program included an elution with 800 mmol/L sodium hydroxide, lasting 10 min, followed by a gradient from 800 to 600 mmol/L, for 10 min, then back to 800 mmol/L for 10 min, and finally a plateau of 10 min at 800 mmol/L. Following separation, the sugars were detected by amperometry at an impulse (pulsative amperometry detector, PAD). The amount of total soluble sugar was determined as the sum of the detected concentrations (C, mg/L) of various polyols and carbohydrate compounds and was expressed in g per 100 g DM: $(100\times C\times V\times \mathrm{DF})/(M\times 1000\times 1000)$, where, V is the volume of the flask used (50 ml), DF is the dilution factor before chromatographic assay, and M is the sample weight (g).

Distilled water was used for all the samples and was obtained from water purified through a Millipore purification system.

2.5 Total phenolic compound content

To assess total phenolic compounds, the Folin-Ciocalteu method was used (Waterman and Mole, 1996). Three grams of frozen native materials (banana pulp or peel) were mixed into 7 ml acetone at 20 °C for 10 min. The mixture was filtered (FT) and 25 µl FT was added to 475 µl water to obtain the crude extract. The 50-µl FT and 3.5-ml water were mixed together and then 2 ml of this mixture was filtered through an OASIS HLB cartridge. Then 4 ml of water was used to rinse the aqueous extract from the cartridge. The absorbance was read at wave length (λ)=760 nm and the results were expressed in mg gallic acid equivalent (GAE)/100 g DM.

2.6 Dopamine analysis

Ten-gram frozen banana peel was mixed in 30% acetone at pH 2.5 (formic acid was used), then filtered through a square (150 mm×150 mm) Legallois filter weighing 73 g/m^2 with 0.17 mm thickness, 17–30 µm porosity with a 22-s time and a 1.25-kg/cm^2 resistance.

The extract was separated on high-performance thin layer chromatographic (HPTLC) plates coated with 250-µm layers of silica gel Merck 60 F254, with *n*-butanol:glacial acetic acid:distilled water 7.0:2.0:1.0 (v/v) as the mobile phase.

A sensitive and accurate HPTLC method was used for the quantification of dopamine (Dighe *et al.*, 2008). One gram of banana powder was extracted with acetone:acidified distilled water using 5% formic acid 7.0:3.0 (v/v).

Dopamine standard (Sigma, France) and sample solutions were applied to the plates in 6 mm bands, spaced 6 mm apart and 10 mm from the bottom edge of the plate, by means of a Camag Linomat V applicator. The plates were developed to a distance of 80 mm from the bottom edge of the plates, with *n*-butanol:glacial acetic acid:distilled water 7.0:2.0:1.0 (v/v) as the mobile phase, in a Camag glass twin-through chamber, previously equilibrated with the mobile phase for 5 min. Densitometric scanning was performed at 280 nm using a deuterium lamp. The scanned data were processed using WinCATS software. Detection was also performed with 0.2% ninhydrin vapor at 105 °C after 5 min. Distilled water was used for preparing all the samples; the solutions and the mobile phase were obtained using a Millipore Milli Q water purification system.

2.7 Statistical analysis

Data were subjected to analysis of variance (ANOVA) using statistical software (Statsoft, Version 7). Differences between means were assessed using Duncan's multiple range test (P<0.05). Analyses were performed on three biological replicates.

3 Results and discussion

3.1 Peel color, peel hardness, pulp firmness, and pulp/peel ratio measurements

The physiological ages of samples represented by 400, 600, and 900 dd exhibited different fruit weights, respectively, (88.02±8.69), (117.88±20.09), and (208.71±21.98) g (P<0.001); the percentages of pulp were (39.6±3.15)%, (53.7±2.56)%, and (60.6±2.07)%, respectively (P<0.001).

Banana fruit harvested at 400 dd and treated with 10000 μl/L of acetylene remained green and never yellowed throughout the postharvest ripening period (2–4 d) while fruit from the same cultivar harvested at 600 or 900 dd displayed a statistically significant (P<0.05) peel color change (Fig. 1). Fruits harvested at 900 dd responded 2 d earlier than those harvested at 600 dd. Furthermore, the color modification (yellow) was denser (data not shown).

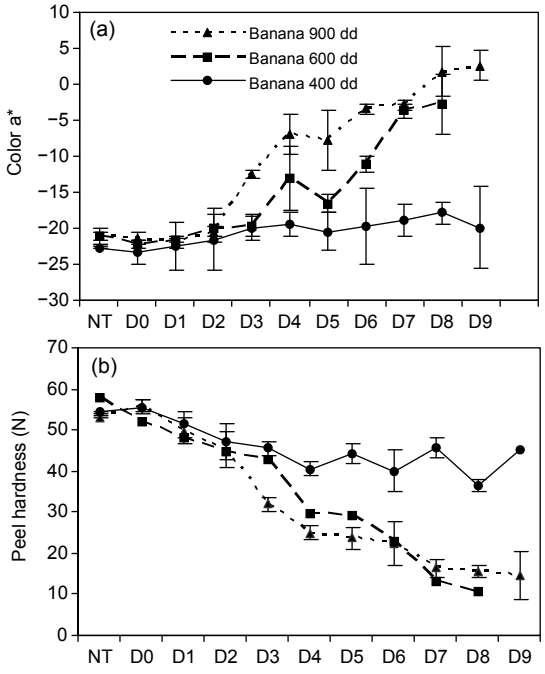

Fig. 1 Comparison of color (a) and peel hardness (b) of 400-, 600-, and 900-dd bananas during ripening (WP)
Data are expressed as mean±standard deviation (SD) with three replicates. NT: untreated fruit taken at harvest time; D0, D1, …, D9: Day 0, Day 1, …, Day 9 after 10000 μl/L acetylene treatment

No marked change in peel hardness or pulp firmness was observed during postharvest ripening of banana fruit harvested at 400 dd. The peel hardness of 600- and 900-dd fruits displayed a similar pattern of change starting on Day 4 [(29.88±4.78) N] and Day 3 [(32.06±3.03) N], respectively.

With regard to pulp firmness, no marked change was observed for fruit harvested at 600 dd. Those harvested at 900 dd exhibited a decrease in pulp firmness from Day 0 [(24.17±1.08) N] to Day 6 [(2.05±0.37) N] after acetylene treatment and remained constant at (2.05±0.37) N after Day 9 (Fig. 2).

During postharvest ripening, the average percentage of pulp was higher for bananas harvested at 600 dd [(53.79±2.57)%] and 900 dd [(60.6±2.07)%] compared to those harvested at 400 dd [(39.61±3.15)%]. The average fruit weight was significantly higher for 900 dd bananas [(208.71±21.98) g with P<0.001] than for 400 dd [(88.02±8.69) g] or 600 dd [(117.88±20.09) g] bananas (Fig. 2).

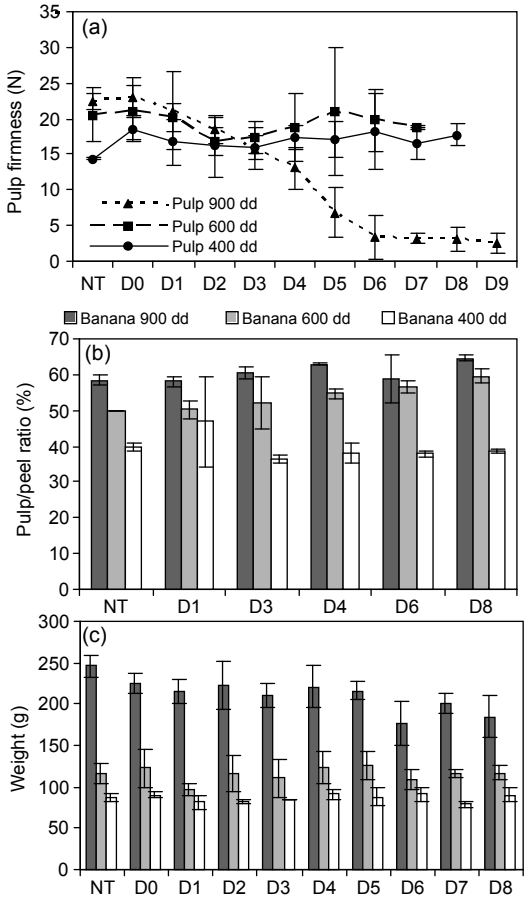

Fig. 2 Characterization of pulp firmness (a), pulp/peel ratio (b), and weight (c) variations of the bananas (*Musa acuminata*, AAA, Cavendish, cv. Grande Naine) at different physiological stages (WP)
Data are expressed as mean±standard deviation (SD) with three replicates. NT: untreated fruit taken at harvest time; D0, D1, …, D9: Day 0, Day 1, …, Day 9 after 10000 μl/L acetylene treatment

The results obtained for 1000 μl/L acetylene treatment (data not shown) generated similar profiles; different acetylene concentrations (1000 or 10000 μl/L) induced only a delay or acceleration, respectively, in ripening.

von Loesecke (1950) classified banana ripening in eight stages according to peel color. Pulp firmness and peel hardness are also valuable parameters as ripening indicators (El-Zoghbi, 1994; Ali *et al.*, 2004; Manrique and Lajolo, 2004). Banana fruit undergoes a climacteric ripening process. Such fruit can ripen independently ex-planta once the ability to respond to ethylene or its analogue (i.e., acetylene) is acquired. Based on these criteria, our data suggest that fruit harvested at 400 dd did not display a change in ripening parameters (i.e., color, peel hardness, and pulp firmness) and therefore had not acquired the ability to ripen and was physiologically unable to ripen whatever the acetylene treatment concentration. Thus, fruit harvested at 400 dd can be considered as immature green fruit in which the physiological mechanism leading to a response to ethylene has not been activated. This is in contrast to fruit harvested at 600 and 900 dd. Our results demonstrate that bananas harvested after 600 or 900 dd are able to ripen partially or fully, respectively, and thus can be considered as mature green fruit. The differences between these two mature green fruits in term of the development of ripening criteria suggest that the physiological mechanism leading to a full response to ethylene and ripening occurs sequentially. This mechanism is partially achieved at 600 dd (early mature green stage) as at that stage the peel yellowed and softened while the pulp remained firm, whereas at 900 dd (late mature green stage), the mechanism is completely activated leading to a fully ripening fruit.

3.2 Starch and soluble sugar evolutions

Banana starch content, before gassing, was significantly higher in fruit harvested at 900 and 400 dd during the DP (Fig. 3). During postharvest ripening of mature green fruit (i.e., 600 and 900 dd), the pattern of starch degradation was similar in fruit harvested at DP and WP. However, climactic harvest period impacted the rate of starch degradation. Indeed, fruits harvested at 600 and 900 dd showed starch-decreasing profiles during postharvest ripening in both the DP and WP. The starch content level drop was significantly greater for the WP than for the DP (74% versus 37% at 900 dd). Conversely, for fruit harvested at 400 dd, the starch content remained stable in both climatic conditions. Soluble sugar profiles were identical in all bananas whatever the climatic period or ripening stage. However, after ripening induction, the soluble sugar content significantly increased in fruit harvested at 600 or 900 dd, whereas it remained stable in those harvested at 400 dd, characterized by the lowest sugar level (Fig. 4). All these results suggest that DP tends to promote starch synthesis in banana during the pre-harvest developmental phase without any impact on soluble sugar content and profile. Ripening, whatever the climatic period, induced a decrease in starch content associated with a concomitant increase in major soluble sugars in bananas harvested at 600 or 900 dd (78% to 88% increase in sugar content for 600- and 900-dd fruit, respectively, compared with 400-dd fruit) yet a very limited or no increase in 400-dd fruit. Starch was reported as the major component of green bananas, and may undergo critical changes during ripening (Cordenunsi and Lajolo, 1995; do Nascimento *et al.*, 2006). Taken together, our observations suggest that in banana, climatic period can influence the initial starch content and its pattern of change during ripening but not the soluble sugar level or its evolution profile post-gassing. Ripening would influence neither the starch nor the sugar content but would have an impact on the change in soluble sugar content in response to ripening induction. This observation was in agreement with our results from peel and pulp analyses. Indeed, contrary to bananas at 400 dd, those harvested at 600 and 900 dd have developed enzymatic ripening ability, and their more mature metabolism induces conversion of starch to soluble sugar after gassing. Therefore, immature green fruit harvested at 400 dd whose inability to ripen prevents starch degradation during postharvest storage appeared as a good raw material for starch extraction in the prospect of food industry valuation.

3.3 Total polyphenol compound content and optimization

Whatever the green developmental stages, total polyphenol content was higher in fruit harvested in the DP than in that harvested in the WP (Fig. 5). The total polyphenol content was also significantly higher

in fruit harvested at 400 dd compared to that harvested at 600 and 900 dd. After 1000 µl/L (data not shown) acetylene gassing, total phenolic compound levels remained stable in the fruit pulp and peel whatever their developmental stages (i.e., 400, 600, or 900 dd). However, 10000 µl/L of acetylene gassing induced a decrease in total polyphenol compound at all developmental stages. The pulp was most affected by this lowering (Fig. 5).

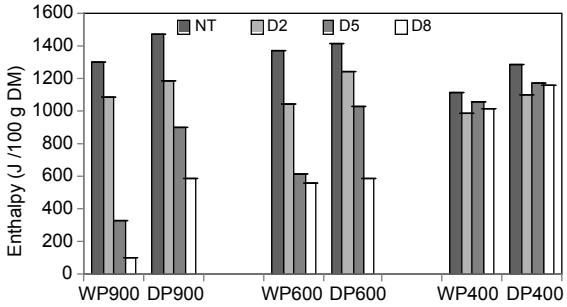

Fig. 3 Modification of enthalpy limits for the WP and DP
The starch content determination was tested for bananas harvested in WP and DP. The results at 10000 µl/L acetylene gassing are shown. NT: untreated fruit taken at harvest time; D2, D5, D8: Day 2, Day 5, Day 8 after 10000 µl/L acetylene treatment; WP900, WP600, WP400: 900 dd, 600 dd, 400 dd in WP; DP900, DP600, DP400: 900 dd, 600 dd, 400 dd in DP

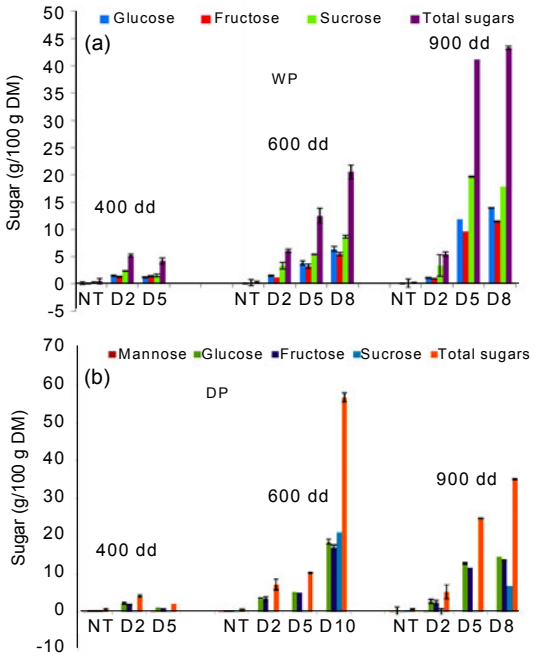

Fig. 4 Soluble sugar variation in FWI Cavendish bananas harvested at the three different physiological harvest stages in both WP (a) and DP (b)
Data are expressed as mean±standard deviation (SD) with three replicates. NT: untreated fruit taken at harvest time; D2, D5, D8, D10: Day 2, Day 5, Day 8, Day 10 after 10000 µl/L acetylene treatment

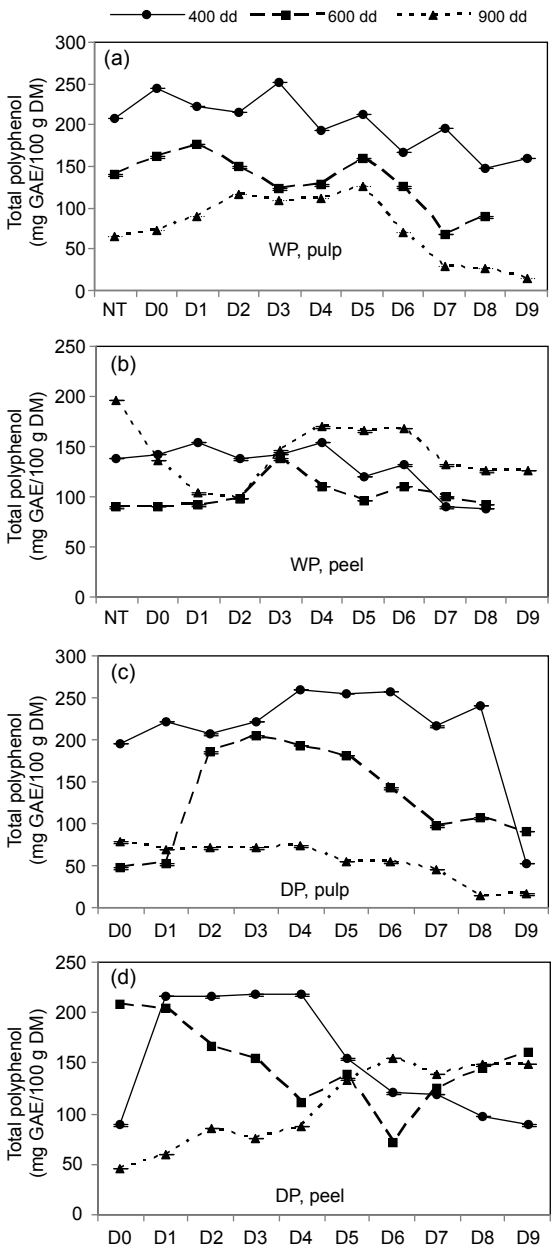

Fig. 5 Total polyphenol profile of fruits (pulp (a, c) and peel (b, d) harvested in WP (a, b) and DP (c, d)
The data were from samples treated with 10000 µl/L acetylene gassing. NT: untreated fruit taken at harvest time; D0, D1, …, D9: Day 0, Day 1, …, Day 9 after 10000 µl/L acetylene treatment

These results suggest that climatic harvest period has an impact on the total polyphenol content with a DP promoting high polyphenol concentration. Also, the pre-harvest maturation process shows a significant inverse correlation with polyphenol content. Immature green fruit contains more polyphenols than

mature green fruit. This correlation is therefore age-dependent. The effect of acetylene treatment was characterized by a decrease in phenolic content in all bananas (400, 600, and 900 dd). This impact was expected for 600- and 900-dd bananas since they are mature green fruits. However, it was surprising to find that immature green fruits (400-dd bananas) that are unable to ripen, responded in the same way as older fruits even though the kinetic was clearly different, with retention of higher polyphenol levels in the first five days following ripening induction. This observation could also suggest that the level of total phenolic compounds is not associated with the capacity of fruit to ripen and, therefore, to respond to ethylene or its analogue (i.e., acetylene).

Thus the decrease in the total phenolic component observed during postharvest ripening could be related more to the fruit developmental stage than to acetylene treatment. It might be concluded that 400-dd bananas showed a clear difference in their metabolic behavior and response to external stimuli, leading to a high concentration of polyphenols that might be consumed later during ripening. There is increasing evidence that ripening processes are controlled by both developmental cues and ethylene, with a concomitant set of specific metabolic pathways (Lelièvre *et al.*, 1997; Giovannoni, 2007; Pech *et al.*, 2008; Seymour *et al.*, 2008). Accumulation of phenolic compounds during ripening of immature (400 dd) and mature green (600 and 900 dd) fruits is in agreement with this assertion. Indeed, the change in phenolic content in immature green fruit unable to respond to ethylene might be under the control of developmental cues while in mature green fruit both ethylene and developmental cues might be involved. Recent progress on the ripening process in banana strongly suggests that the ripening process of banana peel tissue clearly differs from that of the pulp (Domínguez and Vendrell, 1994; Clendennen and May, 1997; Inaba *et al.*, 2007), thus suggesting tissue-specific regulation of the ripening process in this species. Independent of climactic season and fruit physiological stage at harvest, phenol content accumulates differentially in peel tissue compared to pulp tissue during ripening. Thus, the change in phenolic content might be one of the physiological ripening processes that are differentially regulated in peel and pulp tissues.

3.4 Dopamine profile during ripening

High dopamine levels have been reported in banana peels (Kanazawa and Sakakibara, 2000). In our study, although dopamine was also the phenolic compound with the highest concentration, Figs. 6a and 6b indicate that the concentrations of dopamine and total phenolic compounds evolved differently during ripening ($P<0.05$). Independent of the climatic period, banana peel dopamine content was inversely correlated to the green developmental stage and, more specifically, to the maturation stage. However, the

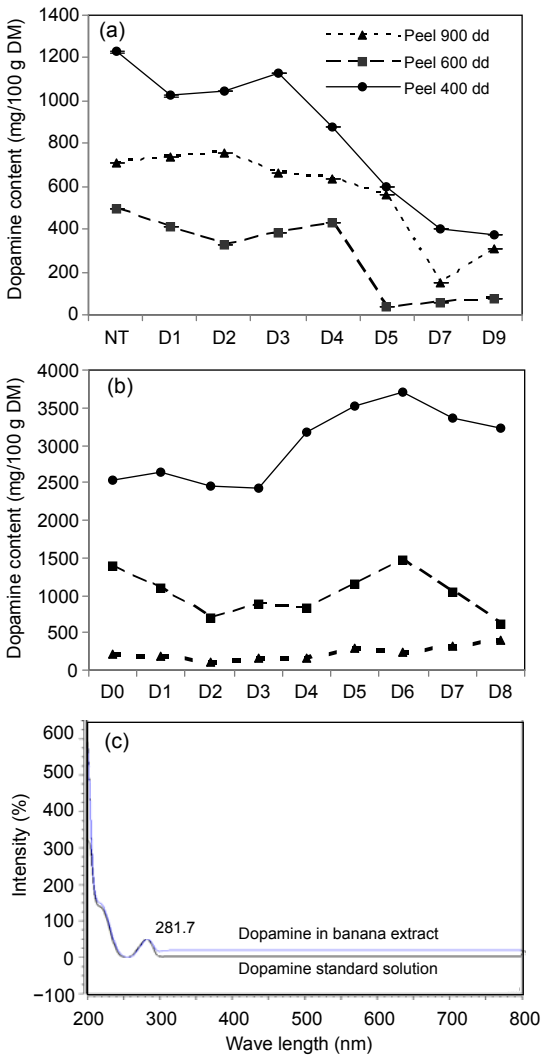

Fig. 6 Dopamine contents in FWI Cavendish bananas harvested in WP (a) and DP (b) and UV spectra of dopamine standard solution and dopamine in banana extract (c)

NT: untreated fruit taken at harvest time; D0, D1, …, D9: Day 0, Day 1, …, Day 9 after 10000 μl/L acetylene treatment

lowest concentration was found in fruit harvested at 900 dd followed by 600 dd, while the highest concentration was obtained at 400 dd. Ripening evolution was characterized by a significant decrease for all developmental stages of fruits harvested during the WP. The pattern was different for fruit harvested in the DP. Indeed, fruit harvested at 400 dd showed an increase in dopamine level 4 d after ripening induction whereas it remained stable for fruits harvested at 600 or 900 dd. The decrease in dopamine content recorded for fruit harvested in the WP might be due to senescence and other mechanisms such as the oxidation of dopamine into salsolinol, as previously suggested by Świędrych *et al.* (2004).

4 Conclusions

The present study showed that pre-harvest parameters influence the chemical composition of bioactive compounds in banana. We also determined that climate impacted starch and polyphenol contents, including dopamine content. A DP was associated with increased bioactive compound concentrations. Furthermore, the maturation stages influenced weight, ripening ability, and polyphenol/dopamine levels with an inverse correlation between maturity and molecule content.

Postharvest parameters also played a role in determining the composition of bioactive molecules in bananas. Indeed, ripening differentially influenced starch, sugar, and polyphenol evolution profiles. These effects may be related to both fruit development stage and climatic conditions.

Taken together, our results provide a basis for selecting the climate conditions, maturation stage, and ripening level for optimal content of target compounds. This offers opportunities for (1) the selection of bananas with the appropriate biochemical status for potential nutrition and health benefits, (2) the extraction of bioactive compounds, and (3) new cultivar selection to promote biotechnology applications.

Acknowledgements

Most experiments were conducted at the Laboratoire de Pharmacologie et Physiopathologie Expérimentale, UMR 95 Qualisud, Faculté de Pharmacie, Université Montpellier 1, France, directed by Prof. Patrick POUCHERET. The authors thank the banana growers of Guadeloupe, France, particularly Mr. Luc POUMAROUX for providing the bananas assessed in this study.

Compliance with ethics guidelines

Christelle BRUNO BONNET, Olivier HUBERT, Didier MBEGUIE-A-MBEGUIE, Dominique PALLET, Abel HIOL, Max REYNES, and Patrick POUCHERET declare that they have no conflict of interest.

This article does not contain any studies with human or animal subjects performed by any of the authors.

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