



**HAL**  
open science

# Review of banana green life throughout the food chain: From auto-catalytic induction to the optimisation of shipping and storage conditions

Pierre Brat, C. Bugaud, C. Guillermet, F. Salmon

## ► To cite this version:

Pierre Brat, C. Bugaud, C. Guillermet, F. Salmon. Review of banana green life throughout the food chain: From auto-catalytic induction to the optimisation of shipping and storage conditions. *Scientia Horticulturae*, 2020, 262, 10.1016/j.scienta.2019.109054 . hal-03488740

**HAL Id: hal-03488740**

**<https://hal.science/hal-03488740>**

Submitted on 21 Jul 2022

**HAL** is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.



Distributed under a Creative Commons Attribution 4.0 International License

1 **Review of banana green life throughout the food chain: from auto-**  
2 **catalytic induction to the optimisation of shipping and storage**  
3 **conditions**

4

5 P. Brat<sup>1,\*</sup>, C. Bugaud<sup>1</sup>, C. Guillermet<sup>2</sup>, F. Salmon<sup>3</sup>

6

7 \*Corresponding author: Dr Pierre BRAT, CIRAD, Département PERSYST, UMR QualiSud,  
8 MUSE, 73 rue J.F. Breton, TA B-95/16, 34398 Montpellier cedex 5, France. Tel: +590 5 90 41  
9 68 32. Fax: +590 5 90 86 80 77. Email address: pierre.brat@cirad.fr

10

11 <sup>1</sup>CIRAD, Département PERSYST, UMR QualiSud, MUSE. 73 rue J.F. Breton, TA B-95/16,  
12 34398 Montpellier cedex 5, France.

13 <sup>2</sup>CIRAD, Département PERSYST, UR GECO, Campus Agro environnemental Caraïbe,  
14 Quartier Petit Morne - BP 214, F-97285 Le Lamentin, Martinique, France.

15 <sup>3</sup>CIRAD, Département BIOS, UMR AGAP, Station de Roujol, F-97170 Petit-Bourg,  
16 Guadeloupe, France.

17

18

19 **Short version of title:** Banana green life Review

20

21 **ABSTRACT**

22 Banana green life (GL) is the time between harvesting and the start of natural ripening. GL  
23 could be considered as a major quality criterion, as it defines whether or not a fruit is suitable  
24 for export and marketing. The ending of GL, when climacteric crisis occurs, is characterized  
25 by autocatalytic ethylene production. Ethylene synthesis and regulation are described. The main  
26 methods for determining GL are based on detecting the CO<sub>2</sub> peak or a decrease in green  
27 pigments, using a spectrometer (NDVI) for the latter. Temperatures during fruit growth and  
28 Black Sigatoka disease are the main pre-harvest factors affecting GL. The former can be  
29 managed by applying the thermal sums concept and the latter by adequate field practices. The  
30 effects of the main exogenous storage parameters (storage temperature, relative humidity,  
31 concentration of ethylene and O<sub>2</sub>/CO<sub>2</sub> ratio in the atmosphere) could be modelled in some cases.  
32 The most effective solutions for extending GL rely on either developing coatings using new  
33 preservative compounds, or designing packaging capable of controlling the temperature,  
34 CO<sub>2</sub>/O<sub>2</sub> ratio and ethylene concentrations in the environment close to the fruits. It was  
35 demonstrated that 1-MCP is not relevant for increasing GL. A global and integrated approach  
36 involving the overall optimization of pre- and post-harvest factors needs to be applied to  
37 maintain green fruit until voluntary/artificial ripening is induced.

38

39 Keywords: banana; green life; ethylene; shipping; storage

40

41

## 42 **1. Introduction**

43 Banana is the fourth most consumed product in the world and approximately 50 billion  
44 tonnes of Cavendish bananas are produced globally every year (FAO, 2018). Bananas are not  
45 grown in Europe and thus need to be imported from the production sites, which are mainly  
46 located in Central and Latin America, and in West and Central Africa. Bananas are harvested  
47 green and ripened in market areas. Fruits that are allowed to ripen on the tree often split, and  
48 tend to be mealy. The pre-climacteric period after harvesting is vitally important for importers  
49 and ripeners, because bananas are transported before they are ripened.

50 During this period, mature green fruit have a low basal respiration rate and ethylene  
51 production is almost undetectable. This period is also called the “green life” (GL) and the  
52 longest practical “pre-climacteric period” is sought (Hailu et al., 2013b). The length of this  
53 period is influenced by several factors, such as temperature, relative humidity (RH) or the  
54 surrounding ethylene concentration. At the onset of fruit ripening in climacteric fruits, such as  
55 banana, a rapid rise in respiration and autocatalytic ethylene production is observed. Indeed, at  
56 this key point, a cascade of enzymes implicated in the ethylene synthesis pathway occurs,  
57 initiating the onset of fruit ripening, hence the end of the GL period. The first section of this  
58 review is therefore devoted to the fruit itself, with special focus on ethylene synthesis auto-  
59 induction mechanisms, the physiology of the fruit, and the correlative prediction of banana GL.

60 GL prediction is of great scientific, but also economic interest, so a dedicated section will  
61 focus on the different approaches and ways of evaluating this quality factor.

62 Field conditions largely affect ripening onset and numerous publications have studied the  
63 influence of agronomic conditions (temperature, fungal pressure, etc.). Indeed, fruit growing  
64 conditions, or disease control on plants in the orchard, will lessen or increase the GL period and  
65 therefore need to be closely considered.

66 Numerous post-harvest treatments and technologies, such as controlled or modified  
67 atmospheres, have been developed to maintain GL duration as much as possible, and thereby  
68 limit potential losses during the fruit shipping and delivery stages. A section will be dedicated  
69 to this and a special section will be developed on management at reefer level.

70 Lastly, post-harvest technology trends for the future will be proposed in order to raise  
71 stakeholder awareness of the need to develop novel and safe ways of optimizing GL in the  
72 coming decades.

73

## 74 **2. Green life at fruit level**

75

### 76 *2.1. Green life ending and occurrence of the auto-catalytic ethylene process*

77

78 As clearly depicted by Dominguez and Vendrell (1993), the ripening of climacteric fruits  
79 such as banana shows a rapid rise in respiration and autocatalytic ethylene production. In these  
80 fruits, ethylene is considered the trigger because exogenous ethylene induces ripening and  
81 inhibition of its synthesis prevents it. They established that the regulation of ethylene  
82 biosynthesis seems to depend on ACC (1-aminocyclopropane-1-carboxylic acid) availability,  
83 but also on the capacity of the tissue to convert ACC to ethylene.

84 The pathway for ethylene biosynthesis was clearly depicted in apple, and other fruits such  
85 as avocado, banana, and tomato by Kende (1993). At the onset of fruit ripening, the expression  
86 of multiple ACC synthase genes is activated, resulting in increased production of ACC, which  
87 is then oxidized to ethylene by ACC oxidase. In most cases, it is the ACC synthase activity that

88 determines the rate of ethylene biosynthesis. In banana fruit, ethylene biogenesis in the naturally  
89 ripening fruit is initiated by some factors involved in the regulation of the ageing process. To  
90 establish the succession of events occurring from the green to the ripening stage, and therefore  
91 to gain a better understanding of the banana GL ending process, the study by Areas *et al.* (1988)  
92 is worth looking at in detail. Ethylene synthesis was enhanced by using protein synthesis  
93 inhibitors meaning that these inhibitors affected the equilibrium mechanisms of ripening at  
94 tissue level. In fact, the capacity for ethylene production, and therefore the climacteric peak, is  
95 often associated with the integrity of the cell membrane integrity. Maintenance of the ethylene  
96 concentration in the fruit tissues under its threshold level during fruit GL might ultimately be a  
97 result of an intensive repair process that is highly dependent on protein synthesis (Areas *et al.*,  
98 1988). The biosynthesis of ethylene from methionine involved two key steps: *i*) the ATP  
99 (Adénosine-Triphosphate) break, which affects the conversion of methionine into S-  
100 adenosylmethionine (SAM) and *ii*) ACC oxidase activation, which affects the conversion of  
101 ACC into ethylene. After harvesting of the fruit, ACC and ethylene production are low in  
102 banana fruit during the pre-climacteric phase. About 0.20  $\mu\text{mol}\cdot\text{g}^{-1}\cdot\text{h}^{-1}$  of ethylene and 0.25  $\text{nmol}\cdot\text{g}^{-1}\cdot\text{h}^{-1}$   
103 ACC were detected in immature banana during the pre-climacteric period (Li and Huang,  
104 1988) and their levels remained nearly constant up to the onset of ripening. At the onset of  
105 ripening, meaning the end of GL, ethylene production and ACC levels increase markedly, with  
106 ethylene production reaching a peak before the respiratory climacteric (Li and Huang, 1988).  
107 Trace amounts of endogenous ethylene may be responsible for the gradual elevation of ACCO  
108 (ACC-oxidase) activity during the pre-climacteric stage (Gao *et al.*, 1990).

109

110 2.2. *Changes in biochemical compounds throughout fruit GL*

111

112           There are only a few papers dealing with changes in fruit composition throughout the GL  
113 period. There are 7 stages in the banana fruit ripening process, with GL covering the first two  
114 stages with, for the Cavendish cv., a sugar content close to 0%, a constantly high starch content  
115 (23 to 25%) and CO<sub>2</sub> respiration ~ 4 mg CO<sub>2</sub>.kg<sup>-1</sup>.h<sup>-1</sup> (Mees, 2017). The only visible parameter  
116 is chlorophyll declining gradually during the green life period and making the peel turn a deep  
117 green to green with a faint hint of yellow.

118           There is no starch hydrolysis during GL and thus we could not relate the changes in fruit  
119 GL to histological changes such as starch hydrolysis (Jullien *et al.*, 2001). The water-soluble  
120 tannin content of banana pulp decreased and then increased during ripening (Chang and Hwang,  
121 1990), while that of banana peel decreased continuously during storage, especially during  
122 ripening. A possible relationship between critically low levels of free indole-3-acetic acid  
123 (IAA), the onset of starch degradation and therefore banana GL, was suggested by Purgatto *et*  
124 *al.* (2002). In relation to starch degradation during banana ripening, IAA levels can be  
125 considered as one of the regulatory factors, or at least a compound that can efficiently delay the  
126 onset of the ripening process.

127

### 128 2.3. *Impact of exogenous factors on the auto-induction of ethylene synthesis*

129

#### 130 2.3.1. Relative humidity storage effect.

131           With storage at 20 °C, the impact of water loss on GL (d) could be estimated by  
132 linearization, the resulting equation being  $GL(d) = 22.15 - [5.3 \times \% \text{ Weight Loss per day}]$  ( $p$   
133  $< .001$ ) (Littmann, 1972). As a result, for a shipping time of ~10 d and a total fruit weight loss  
134 of 10% after shipping, GL was reduced from 22 to 16 d. Finger *et al.* (1995) also confirmed the

135 effects of water loss on banana fruit GL (*Musa accuminata* Colla), a water loss of 5% leading  
136 to a shortening of GL in pre-climacteric fruits. In fact, ethylene production in pre-climacteric  
137 fruits was stimulated by water stress, causing an increase in respiratory metabolism, such as  
138 observed in vegetative tissues. It is likely that the ethylene induced by water stress triggered  
139 autocatalytic ethylene production by the fruit and the climacteric rise of respiration. Indeed, it  
140 is commonly accepted that maintaining fruits at a low relative humidity (RH) accelerates water  
141 loss and also causes earlier changes in respiration and ethylene production (Burdon *et al.*, 1994).  
142 A gradual increase in the ACO activity of pulp and peel stored at a high RH was also observed.

143

#### 144 2.3.2. Storage temperature effect.

145 At room temperature, fruit respiration is maintained at the normal level, but if the fruit is  
146 stored at a lower temperature, fruit respiration will be reduced, resulting in a decreased of ATP,  
147 hence reduced ethylene biosynthesis. The purpose of storage temperature control is therefore  
148 to limit fruit respiration by suspending ethylene biosynthesis, thereby extending fruit post-  
149 harvest life, including green life. Fruit GL bears an inverse linear relationship to the temperature  
150 at which fruit are kept. An average regression equation established on the average of 4  
151 experiments was determined (Wills *et al.*, 2001) as  $GL(\text{day}) = [-0.97 \times \theta] + 93$  ( $\theta$  storage  
152 temperature in °F). Thus, at 55 °F (12.8 °C) and 59 °F (15 °C), the expected GL was estimated  
153 at 40 and 36 days respectively, meaning that a 1 °F increase during storage reduces potential  
154 GL by one day. Blake and Peacock (1971) extended these former findings to higher  
155 temperatures (60 °F (15.5 °C) to 96 °F (35.5 °C)) and obtained the following regression  
156 equation  $GL(d) = 10^{[-(0.02529 \times T \text{ °F}) + 2.898]}$  meaning that at 15.5 °C (60 °F) the estimated GL of  
157 the fruit was 24 days. A 12 days difference in GL was therefore obtained applying the two



158 regression equations mentioned above, highlighting the precaution that should be taken if using  
159 it.

160 The high sensitivity of banana fruit to the duration and intensity of low temperatures that  
161 could provoke chilling injury (Jackman *et al.*, 1988) should be kept in mind at all times to  
162 effectively match the constraints in the banana supply chain. Indeed, considering the shipping  
163 duration (usually 10 to 20 days), hence the long cold-stress induced, the air-shipping  
164 temperature of the reefer at 12.5-13 °C should really be considered as a critical value, hence a  
165 limit for possibly extending GL. With a view to curtailing post-harvest losses and extending  
166 fruit availability, Gonge *et al.* (2013) studied the combined effect of harvest maturity stages and  
167 storage temperatures throughout the shipping of bananas (cv. Grande Naine). The greater the  
168 physiological age is at harvest the lower is the GL (Table 1). Indeed, harvesting bunches at 90%  
169 of the total maturity allows the GL to increase to 2 or 3 days, this behaviour being confirmed  
170 whatever the storage temperature (14 or 16°C). Even if potentially interesting in terms of GL  
171 extension, 12 °C implies chilling injury and is therefore not recommended. Joas (1987)  
172 estimated the potential GL reduction at 7-8% of GL for a 1 °C higher storage temperature,  
173 whatever the maturity at harvest, and therefore partially confirmed the data previously  
174 presented (~ 4 days lost from 12 to 14 °C storage T °C). As a conclusion at this point, the faster  
175 the fruit can be cooled after harvesting, then the longer would be the expected GL, the fruit  
176 being less sensitive to any ethylene present in the post-harvest chain (Turner and Fortescue,  
177 2012).

178 Table 2 presents an overview of the regression equations established to estimate the  
179 potential GL of banana depending on the limiting temperature and CO<sub>2</sub> conditions. Averaging  
180 the equations resulting from different studies, at 13°C the estimated GL is ~35 days and is  
181 reduced by 3 days for a 1 °C increase in storage, which tallies well with the 7-8% GL time  
182 reduction for 1 °C higher proposed by Joas (1987).

183

184 2.3.3. Light effect.

185 Although not specifically demonstrated for banana, it has been reported for many years  
186 that light decreases the amount of ethylene produced (Sisler and Wood, 1988). The level of  
187 ethylene production could be stimulated above the dark level when both CO<sub>2</sub> and light were  
188 supplied. While maintaining the fruit at an ethylene concentration below 0.005 ppm, banana  
189 GL was reduced by ~50% when the fruit was exposed to light. The response did not seem to be  
190 dependent on the physiological age at harvest and was greatest when exposure started  
191 immediately after harvest (Peacock, 1972). Although this aspect is not relevant for bananas as  
192 they are of course shipped in boxes in the reefer, therefore in the dark, this tendency could help  
193 in understanding fruit green life behaviour in relation to mechanisms induced by ethylene.

194

195 2.3.4. Effect of O<sub>2</sub> and CO<sub>2</sub> concentration during storage.

196 The submitted hypothesis in view of the apparent role of CO<sub>2</sub> in facilitating the  
197 conversion of ACC into ethylene was that illuminated thylakoid membranes also convert ACC  
198 into ethylene, and that this conversion can be stimulated by added bicarbonate. However, since  
199 this reaction only occurs in the light, it is presumably free radical-mediated and non-enzymatic.  
200 The review by Sisler and Wood (1988) tried to clear up the controversial effect of CO<sub>2</sub>, finding  
201 that low levels of carbon dioxide regulate ethylene synthesis and higher levels inhibit ethylene  
202 action. It seems, in fact, that CO<sub>2</sub> counteracts the effects of ethylene in many cases but it can  
203 also stimulate ethylene production by increasing the amount of ACC compared to ethylene, and  
204 by increasing the activity of that enzyme (Bufler, 1986).

205 The importance of oxygen concentration in the storage atmosphere for controlling banana  
206 fruit ripening is very important. It is indeed possible to prevent any synthesis of ethylene, above  
207 the minute amounts found emanating from unripe fruit, by storing the fruit in oxygen  
208 atmospheres containing not more than 7.5% oxygen at the normal ripening temperature (18 °C).  
209 Under such conditions, the oxygen tension is sufficient to prevent either injury and will not  
210 impart taste or flavour to the fruit.

211 Combined storage in reduced oxygen and increased carbon dioxide reduced respiratory  
212 activity during storage and thereby boosted banana GL. The lowest weight loss was established  
213 at 2% O<sub>2</sub> and 4 to 8% CO<sub>2</sub>, with the weight loss for 14 storage days being reduced by more than  
214 37% using this controlled atmosphere (Hailu *et al.*, 2013). We can confirm that this specific gas  
215 composition helps to optimize banana GL during storage. Indeed, Jedermann *et al.* (2014b)  
216 confirmed that elevated CO<sub>2</sub> (5%) and low O<sub>2</sub> (2%) concentration in storage vessels led to an  
217 increase in average green life of 4 d at 15 °C and 11 d at 18 °C.

218 To obtain these required O<sub>2</sub> and CO<sub>2</sub> target values, use of the controlled or modified  
219 atmosphere is the only way of maintaining this gas composition throughout the shipping phase.  
220 Modified atmosphere (MA) packaging, created by the respiration of the fruit itself inside a bag  
221 having specific O<sub>2</sub>/CO<sub>2</sub> permeability, is recognized as an easy and inexpensive method of  
222 extending banana GL compared to the controlled atmosphere. Chamara *et al.* (2000) used Low  
223 Density Polyethylene bags (LDPE) as a packaging system to extend storage life, thus creating  
224 a modified atmosphere able to extend the storage life of banana (cv. Kolikuttu). Stewart *et al.*  
225 (2005) improved this system by using silicone membrane and diffusion channel systems to  
226 provide suitable conditions for optimum storage of Giant Cavendish bananas. As a result, they  
227 achieved levels of 3.5% CO<sub>2</sub> and 3% O<sub>2</sub> in about 10 d using this membrane, with these gaseous  
228 conditions being rather close to optimum conditions for banana (2% O<sub>2</sub> and 4 % CO<sub>2</sub>, Hailu *et*  
229 *al.* (2013)).

230 Table 3, extracted from the study by Jedermann et al. (2014b), can be considered as a  
231 good summing up of the relative humidity, temperature and modified atmosphere effect at  
232 reefer level. Using extreme conditions, namely 18 °C in dried air as opposed to 15 °C in a wet  
233 atmosphere at 5% CO<sub>2</sub>, reduced fruit GL to around one third of its original potential.

234 Considering that the RH inside Low Density Polyethylene bags during the shipping of  
235 fruits with a conventional perforation density of 0.01 dm<sup>2</sup>.m<sup>-2</sup> (4 holes in a conventional  
236 polybag), is higher than 99%, each additional degree during storage from 15 to 18 °C reduces  
237 GL by 5 d or more. The detrimental effect of a low RH is indeed again highlighted, since at 15  
238 °C the measured banana GL will drop from 48 to 42 d in normal air at a 50% RH. Lastly, the  
239 positive effect of a high CO<sub>2</sub> concentration (5%) in terms of GL extension seems to be more  
240 intense at a high storage temperature (18 °C).

241

#### 242 2.3.5. Effect of ethylene concentration during storage.

243 Ethylene, which is auto-catalytically synthesized at levels as low as 0.01 µL.L<sup>-1</sup>, triggers  
244 the ripening process (Prasanna *et al.*, 2007). It should be noted that while this observation is  
245 commonly accepted, the threshold of ethylene concentration likely to initiate the ripening  
246 process is debatable. Indeed, the ethylene concentration needed to initiate banana fruit ripening  
247 is highly dependent on the physiological age at harvest (sometimes called maturity at harvest)  
248 and on the storage temperature. In fact, it is unambiguous that there is no threshold of ethylene  
249 concentration for ripening, but instead that several factors such as ethylene contact time. The  
250 physiology of the fruit at harvest or the temperature background are the key factors delimiting  
251 fruit GL (Wills *et al.*, 1999). Indeed, for a long time, a lower ethylene limit that could initiate  
252 fruit ripening was discussed and the limit of 0.1 ppm (Inaba and Nakamura, 1988) was  
253 commonly accepted in the banana chain for many years. The study by Wills et al. (2001)

254 confirmed banana to be one of the most ethylene-sensitive climacteric fruits. By fixing two  
255 limits, a 10% loss in storage life that could be tolerable in most marketing situations, and a 30%  
256 loss that could limit marketing opportunities, the authors established a regression equation at  
257 20°C for banana GL (d) = [- 9.24 x Surrounding Ethylene Concentration] + 3.3. It appears  
258 therefore that the marketing limit (30%) is reached with less than 0.03 ppm, while the tolerable  
259 marketing limit (10% loss) will be at less than 0.01 ppm. Note that this value is not so far from  
260 the limit of detection used in this paper, which was 0.005 ppm. Furthermore, the authors  
261 established that 0.1 ppm, formerly accepted as a limit ethylene value, provoked a ~50%  
262 reduction in GL under these conditions.

263 A reduction in surrounding ethylene concentration as a trigger to maintain or extend  
264 banana GL was extensively studied by Wills et al. They investigated the impact of a wide range  
265 of ethylene concentrations, ranging from rather high to ultra-low, during storage using different  
266 banana cultivars from Australia (Wills et al., 1999). It appeared that, whatever the cultivar, GL  
267 at 20 °C does not exceed 4 days at 1 ppm of ethylene, while rising to ~ 11 d at 0.1 ppm, ~24 d  
268 at 0.01 ppm and, lastly, more than 33 d at 0.001 ppm. However, these extremely low ethylene  
269 concentrations are not reachable in the food chain, even using specific ethylene absorbers in the  
270 cardboard box, or at reefer level. Wills and Golding (2015); Wills *et al.* (2014) quantified the  
271 relationship between ethylene concentration, temperature and GL of Australian-grown  
272 Cavendish bananas. Fruits were stored at 15, 20 or 25 °C in air containing 1.0, 0.1, 0.01 or  
273 0.001 ppm ethylene, and green life was taken as the number of days to reach the respiratory  
274 climacteric. They found that banana green life decreased with increasing storage temperatures  
275 and ethylene concentrations according to the relationship:  $GL (d) = 5.74 - (21.81 \times X) - (0.82 \times$   
276  $X^2) - (0.097 \times Z) + (0.55 \times Z)$ , where X = log of ethylene concentration (ppm) and Z = storage  
277 temperature (°C). These authors concluded that it would not seem unreasonable to expect that

278 keeping bananas at a low ethylene concentration would give a similar post-harvest life as at low  
279 temperatures in current commercial situations, where ethylene levels can readily accumulate.

280

### 281 **3. GL determination and forecasting**

282

283 If we consider that GL is the time interval between the harvest date and the initiation of  
284 the climacteric phase. This associated end-phase is therefore correlated both with an increase  
285 in respiratory intensity with CO<sub>2</sub> exhausted from 10-20 mg CO<sub>2</sub>.kg<sup>-1</sup>.h<sup>-1</sup> to 60-120 mg CO<sub>2</sub>.kg<sup>-1</sup>.h<sup>-1</sup>,  
286 and with degreening of the peel associated with chlorophyll degradation. Any  
287 determination methods are based on these physiological changes. Chillet *et al.* (2008) detected  
288 the climacteric peak of a banana placed in a semi-permeable container, through an analysis of  
289 O<sub>2</sub> and CO<sub>2</sub> levels resulting from fruit respiration. This method allowed accurate measurement  
290 ( $\pm 1$  d) of GL compared to methods based on fruit colour or decrease in texture. Anyway, the  
291 successive phases: ethylene auto-induction and respiration peak, and green colour and texture  
292 decreasing range no more than 2 d, this time day difference being far less the GL distribution  
293 among the fruits of a single bunch.

294 New spectrometric methods have been developed to limit the two main limitations of the  
295 methods described above. These spectral approaches are not destructive and can therefore be  
296 applied directly on the fruit still attached to the bunch in the orchard; they give an immediate  
297 response while the former method needs, by principle, to wait for the end of GL. Among criteria  
298 for determining the end of green life, the parameter NDVI (normalized difference vegetation  
299 index) was measured with a hand-held spectrometer (Pigment Analyser, CP Falkensee,  
300 Germany) (Praeger *et al.*, 2013). NDVI indicates chlorophyll content in plant material and is  
301 calculated from the reflected light intensity  $I$  in the following manner:  $NDVI = (I_{780\text{ nm}} - I_{660\text{ nm}})$

302 / ( $I_{780\text{ nm}} + I_{660\text{ nm}}$ ) (Richardson *et al.*, 2002; Zude *et al.*, 2009). The NDVI values for green  
303 bananas at ripening stage 1, just after harvest, vary from 0.3 to 0.2, while at the end of GL  
304 NDVI falls between +0.05 and -0.05. This pigment analyser, which gives the NDVI value,  
305 could therefore be considered as a potential tool for directly and instantly giving a good  
306 estimation of the potential GL of the fruit in the orchard. It should however be validated on  
307 large fruit samples including different physiological ages at harvest, disease severity or shipping  
308 conditions.

309

#### 310 **4. GL optimization in the orchard**

311 In general, any action that involves physiological stress on a fruit causes a reduction in  
312 the pre-climacteric period, which can be associated with increased ethylene production  
313 resulting from the stress. Extremes of temperature, fungal infection, exposure to light,  
314 dehydration and mechanical injury are all common causes of stress during normal commercial  
315 operations that reduce the pre-climacteric period of banana.

316

##### 317 *4.1. Pre-harvest factors affecting GL in the field*

318

##### 319 4.1.1. Nutrients and agronomic conditions management.

320 Excess nitrogen produces crops with smaller fingers and bunches, and reduced their  
321 conformity. Bunches can be poorly filled and have a reduced GL if harvest occurs too late  
322 (Robinson, 1996). For instance, Srikul and Turner (1995) reported that fertilising with 450 kg  
323 N.ha<sup>-1</sup>.year<sup>-1</sup> increased the relative fruit growth rate of cultivar “Williams” (Cavendish

324 subgroup) bananas by 7% ( $P < 0.05$ ) and hasten the relative loss of GL by 46% ( $P < 0.05$ ).  
325 From 0 to 300 kg N.ha<sup>-1</sup>.year<sup>-1</sup>, N had no significant effects on fruit growth or GL. Robinson  
326 (1996) also mentioned that excess of manganese in leaves leads to a reduction in green shelf-  
327 life, thus contributing to the disorder known as "ripe mixture". Lastly, calcium, known to  
328 increase the shelf-life of some fruits, such as apples does not seem to be efficient on bananas  
329 (Tixier *et al.*, 2010). Lastly, calcium is known to strengthen cell tissue and thus can increase  
330 the shelf-life of some fruits, such as plum fruits (Sinha *et al.*, 2019). However, it does not seem  
331 to be the case with bananas as Tixier *et al.* (2010) showed that applications of calcium in the  
332 field, by fertilization or spraying, had no influence on the GL of Cavendish and CIRAD 920  
333 hybrid bananas.

334 As revealed by Mahmoud and Elkashif (2003), plant spacing has a significant impact on  
335 fruit GL. The wider spacing resulted in significantly longer green life than the closer spacing in  
336 both the plant and ratoon crops. This was because plants grown at a wider spacing produced  
337 large, well developed bunches with large fingers which were more likely to have a longer green  
338 life than those produced at a closer spacing.

339

#### 340 4.1.2. Water stress.

341 Water management is one of the first factors to consider in expressing the potential of  
342 banana. Excess water weakens fruit and may result in a short GL (Lassoudière, 2007).  
343 Conversely, a water deficit imbalances the fruit growth/development ratio, thus fruits will be  
344 often harvested at a higher physiological stage which means a lower GL. Srikul and Turner  
345 (1995) reported that a soil water deficit can reduce GL by 48% ( $P < 0.05$ ) in a semi-arid  
346 environment. Indeed, exposure of the roots to drying soil changes the chemistry of the fruit and



347 could eventually cause a small increase in respiration rate.

348

349 4.1.3. Management expertise.

350 Among pre-harvest factors that could reduce fruit GL, an important necrotic leaf area  
351 and/or a low leaf/fruit ratio on the plant are the two main parameters. Indeed, when this ratio is  
352 unfavourable, it will take longer to reach the minimum commercial fruit size, fruit harvesting  
353 will be consequently delayed and finally GL reduce

354 In a study of the factors affecting the post-harvest life of plantains, Ferris *et al.* (1993)  
355 found that out of the genotype, mechanical damages is the most significant factor that affect  
356 GL at the pre-harvest stage. Indeed, increasing peel permeability to water vapour, this exposes  
357 the fruit to increased water stress, which initiates early ripening.

358

359 4.2. *GL and harvest point optimization*

360 Physiological age could be a good indicator of the fruit GL at harvest (Jullien *et al.*, 2008).  
361 For a long time, the harvest point was determined by the fruit grade measurement directly on  
362 the bunch or by the fruit age in number of weeks after flowering (Marin *et al.*, 1996). For  
363 instance, the minimum Cavendish fruit grade (diameter measured in the middle section  
364 perpendicular to the plane) in the French West Indies is 32 mm but it can rise to 36-39 mm for  
365 the *Musa Goldfinger* variety with an adequate GL (Thompson, 2011). These methods  
366 unfortunately do not take into account the seasonal effect, temperature variation or altitude. An  
367 approximate linear relation ( $R^2 = -0.87$ ) between GL and the bunch development period of  
368 different cultivars and clones was already established (Ganry and Meyer, 1975). The established  
369 regression coefficient for the cv. Valery was meaning, for instance, that for harvesting 95 d

370 after flowering, the estimated fruit GL is 28 d at 13.5 °C and that a one-week delay in bunch  
371 harvesting would reduce GL by approximately 3 d.

372 On the basis of the harvest thermal-sum method (i.e. daily sum of average temperature at  
373 the orchard since inflorescence emergence with a zero basis at 14°C) (Umber *et al.*, 2011), these  
374 former limitations could be avoided. An harvest point really representative of the outer  
375 temperature and of the minimum Cavendish growth temperature could be provided. To ensure  
376 a GL of not less than 25 d at 98% RH, the recommended thermal sum for Cavendish is  $900 \pm$   
377  $50$  dd (degree.day) (Ganry and Chillet, 2008). Jullien *et al.* (2001) confirmed that fruit GL  
378 correlates well with bunch age expressed in dd accumulated since inflorescence emergence. In  
379 actual production conditions, the harvest determination method used in the FWI to ensure EU  
380 banana export potential is a compromise between the grade measurement and thermal sum  
381 methods. Indeed, to ensure an optimized yield, but avoiding any risk of ripening in the reefer  
382 during sea-shipping, the thermal sum is only used as a limit not to be exceeded, but bunches  
383 could be earlier harvested if the grade of the fruit reaches the required value.

384

#### 385 4.3. *GL optimization at bunch level*

386

387 Banana bunch covering using thin plastic (low density polyethylene) at flowering is a  
388 physical protection method that improves the visual quality of fruit by promoting skin  
389 coloration and reducing blemishes. It can also change the micro-environment for fruit  
390 development, which can have several beneficial effects on internal fruit quality (Santosh *et al.*,  
391 2017). Jullien *et al.* (2008) showed that a difference of 2 °C between the air temperature inside  
392 and outside the bag was measured. They also showed that plastic bags induce a difference in  
393 accumulated dd between older fruits at the top of a bunch and younger fruits at the bottom. The

394 earlier the bagging date, the larger is the difference in dd, and therefore in GL. Research reports  
395 on fruit bagging have given contradictory information on the effect of bagging on both the  
396 physical and compositional quality of fruits. Kimani *et al.* (2017) mentioned that bunch covers  
397 did not significantly influence GL ( $p>0.05$ ).

398         The solution of 'sealed' bunch cover should be emphasized since this hermetic bag adds  
399 the effect of modified atmosphere (MA) (Johns and Scott, 1989a). Atmospheres of 1.5-3% O<sub>2</sub>  
400 and 5-10% CO<sub>2</sub> have been claimed to be optimum for modified atmosphere within the sealed  
401 bag storage of pre-climacteric bananas at 20 °C. However, the MA requirements of growing  
402 bunches could differ markedly from the MA storage requirements of harvested fruit (Johns and  
403 Scott, 1989a). Unfortunately, leakage is almost unavoidable, even under shed storage  
404 conditions and consequently, the selective permeability of the polyethylene will be offset by  
405 the non-selective nature of the leaks (Wade and Graham, 1987). The bunch/bagging effect on  
406 GL was improved by Johns and Scott (1989b), who established that the inclusion of KMnO<sub>4</sub>  
407 in sealed covers, creating a modified atmosphere at bunch level, increased GL by an average of  
408 8 d.

409

#### 410 4.4. *Seasonal effect*

411         According to Marin *et al.* (1996) and despite of similar grade and age, GL was different  
412 between fruit harvested at different times of the year. Fruit harvested at the hot and dry season  
413 had a longer green life than those harvested during “rainy” winter in Costa-Rica. Seasonal  
414 transition seems to have an impact on the reduction of the pre-climacteric period for fruit  
415 developing rapidly initially and maturing slowly (summer/winter transition). The effect of  
416 climatic factors was later studied by Bugaud *et al.* (2007), who did not find any correlation  
417 between climatic conditions and the GL of bananas harvested at a constant physiological age.

418 These results well matched with those previously obtained by Bugaud *et al.* (2006); Chillet *et*  
419 *al.* (2006), who showed that climatic variations had no significant impact on the GL of bananas  
420 harvested at the same temperature sum. It seems, in fact, that the shortening of GL during the  
421 hot wet season was probably more due to the higher Sigatoka disease pressure during that  
422 season.

423

#### 424 4.5. *Black Sigatoka disease management*

425

426 Sigatoka Disease (SD) and Black Leaf Streak Disease (BLSD), caused by the pathogenic  
427 fungi *Mycosphaerella musicola* and *Mycosphaerella fijiensis*, respectively, are the only biotic  
428 stress in the field known to have an impact on GL (Chillet *et al.*, 2006). Both pathogens affect  
429 banana leaves, thus reducing the photosynthetic surface area, but also affect fruit physiology  
430 and reduce post-harvest GL, up to field-ripe fruit in case of higher infestations (Castelan *et al.*,  
431 2012). A number of studies were conducted to understand this effect, but until recently most of  
432 them had been conducted on SD. As BLSD is more aggressive, and is becoming predominant  
433 in most tropical countries (De Lapeyre de Bellaire *et al.*, 2010), a few specific studies are  
434 available on its relation with GL.

435

##### 436 4.5.1. A reduction related to disease damages.

437 A reduction in GL is often related to an indirect effect of SD, through the reduction of leaf area.  
438 The fewer leaves present on the plant during the flowering-harvest period, the lower the GL is.  
439 A minimum of 3 to 4 leaves at harvest for minimum quality fruit and to ensure fruit shipping  
440 potential is commonly recommended. Ramsey *et al.* (1990) and Daniells *et al.* (1994) even

441 stated that a minimum of 10 leaves at harvest was necessary to prevent premature ripening, with  
442 all bunches having fewer than 4 viable leaves at harvest were field-ripened. This share  
443 decreased logistically as the number of viable leaves at harvest increased up to 10 leaves. A  
444 reduction in the number of leaves below 6 leaves after flowering through severe leaf pruning  
445 was also linked to a reduction in GL by Robinson *et al.* (1992). As a consequence, the number  
446 of leaves at the harvesting stage seemed a practical criterion that is easy to control in the field  
447 for evaluating potential fruit GL, and for limiting the ripening risk during transit (Ramírez *et*  
448 *al.*, 2008). Until now, exporters have often determined a number of leaves as a threshold  
449 (usually 4 to 5 viable leaves at harvest) beyond which fruit should not be exported, or the harvest  
450 grade must be reduced, to supposedly avoid fruit ripening during transit. However, this criterion  
451 has proved to be highly empirical, and has often led to unsuitable decisions.

452 The qualitative descriptions of SD levels related to GL reduction was known for a long  
453 time. Premature ripening occurred at very low spotting levels, at least eight leaves without  
454 spotting should remain at harvest to ensure an optimized GL (Stover, 1974). Yet, this level is  
455 seldom reached under production conditions, and only in regularly sprayed fields and/or under  
456 dry climatic conditions. However, it should be noted that in most of these first studies, fruits  
457 were harvested following a calliper grade threshold and/or the number of weeks between  
458 flowering and harvest, without considering their physiological age. It is possible that, in some  
459 cases, fruits from infested plants took more time to reach harvest grade, and thus were  
460 considerably more mature than indicated by size and appearance at the time of harvest, with a  
461 lower potential GL.

462 Taking into account the physiological age of the fruit at harvest by the thermal sum  
463 method, Ganry and Chillet (2008) proved that quantitative evaluations of the disease level were  
464 more correct in predicting GL than the qualitative or indirect effects of the disease. Chillet *et*  
465 *al.* (2009) confirmed that SD had a direct effect on banana GL through the harvesting of fruits

466 at the same physiological age. Under these conditions, GL decreases as SD pressure increases,  
467 even though the fruits have an identical diameter, proving that the reduction in GL is not caused  
468 by a trophic effect, but rather by a direct effect of the disease. The best disease level indicators  
469 for GL are quantitative: the disease severity indexes at flowering and at harvest. Even though  
470 BLSA is more aggressive than SD, the same results were obtained with BLSA, with no greater  
471 reduction in GL than for SD (Castelan et al., 2012). A linear negative relationship between  
472 disease parameters and GL was further established for SD by Castelan *et al.* (2013): the SD  
473 effect is gradual and continuous, with no threshold effect. Such work has not yet been conducted  
474 for BLSA, but it can be assumed that the same observation would be made.

475 In addition to the severity of the disease, the duration of the disease is also critical for its  
476 impact on GL. Under southern tropical conditions in Brazil, with a longer flowering-harvest  
477 period (FHP), the reduction in GL was drastic in plots highly infested by both SD and BLSA,  
478 with only field-ripened fruits at the time the bunches reached 960 dd (Castelan et al., 2012).  
479 Thus, the longer the disease stays on the plant, the greater is the reduction in GL.

480

#### 481 4.5.2. Potential of agronomic practices as a tool to limit this stress.

482 Some sanitary practices, such as deleafing (or leaf pruning), which consists in  
483 systematically eliminating all necrotic parts of the leaves by cutting them off, proved to be  
484 efficient in limiting the negative effect of SD and BLSA on GL. Necrotic leaf removal from  
485 SD-infested plants led to a large reduction in SD effects on fruit quality, preventing premature  
486 ripening (Chillet *et al.*, 2013). This technique allowed the harvesting of bunches with as few as  
487 3 leaves at the time of harvest. The same observation was made by Guillermet *et al.* (2016) on  
488 BLSA under both humid and dry tropical conditions. Under these conditions, strict elimination  
489 of necrotic tissue, and adequate cultural practices including optimal plant growth and harvesting

490 time, allowed the exporting of bunches with as few as no leaves at harvest, without ripening in  
491 transit.

492 These results show that systematic removal of necrotic parts of leaves can be an efficient  
493 technique for limiting production losses. It furthermore reveals that the presence of necrosis  
494 from SD or BLSD is responsible for GL reduction, whatever the number of leaves at harvest.  
495 Thus, this criterion might not be the most appropriate for evaluating bunch suitability for export.  
496 It also highlights the existence of a potential “stress signal” emitted by necrosis, and directed  
497 to the bunch, responsible for the reduction in GL. The longer this signal is emitted, hence the  
498 longer the necrosis stays on the plant, the greater is the reduction in GL (Castelan et al., 2012).  
499 The timing of the signal also seems critical.

500

#### 501 4.5.3. Markers of GL reduction and hypothesis on the nature of the stress.

502 For both SD and BLSD, GL reduction is associated with an altered maturation process in  
503 the fruit. Although the initial rate of ethylene production is identical in fruits from infected or  
504 uninfected plants, fruits from infested plots show higher emissions of CO<sub>2</sub> and C<sub>2</sub>H<sub>4</sub> production  
505 at the time of the climacteric peak (Castelan et al., 2012). This elevation is higher for BLSD  
506 than for SD. BLSD is also involved in modifications to the starch metabolism during ripening,  
507 and the enzymatic activities linked to its degradation (Saraiva *et al.*, 2013).

508 So far, only hypotheses can be put forward regarding the origin of this “stress signal”.  
509 The synthesis of metabolites by the fungus could have a direct impact on fruit physiology. Some  
510 toxins, such as juglone, are secreted by *M. fijiensis* and involved in the BLSD infection process  
511 (Chuc-Uc *et al.*, 2011; El Hadrami *et al.*, 2005). Ethylene is also produced by diseased tissues,  
512 but is unlikely to be transported very far in the plant, and is probably quickly lost in the air.  
513 Secondary plant metabolites involved in host-pathogen relationships could also impact fruit

514 ripening, as has been shown for methyl-jasmonate and salicylic acid on other pathosystems  
515 (Fan *et al.*, 1998). Lastly, changes in hormone balances, such as indole-3-acetic acid and  
516 gibberellic acid following pathogen infection, may also have an effect on fruit quality (Saraiva  
517 *et al.*, 2013). It is probable that these factors are not exclusive, but act in synergy on processes  
518 leading to GL reduction.

519 To conclude, Sigatoka diseases are an essential factor to consider in most banana  
520 producing countries in order to manage fruit post-harvest quality. A better understanding of  
521 changes in the physiological metabolism induced by these diseases could enable adequate  
522 practices, in order to avoid the stress or interrupt its transmission to the fruit. More generally,  
523 additional work is needed on BLSA in order to quantify its impact on GL, and potentially adapt  
524 management practices.

525

526

## 527 **5. Post-harvest fruit treatment to optimize GL potential**

528

### 529 *5.1. Fruit damages and post-harvest fungal diseases effect*

530

531 Peel abrasion was proved to be negatively correlated to fruit GL (Santana Llado and  
532 Marrero Dominguez, 1997). These authors varied mechanical injury by peeling the fruit surface  
533 at different degrees of severity (0, 1 and 4 cm<sup>2</sup>) and observed GL shortening, which was also  
534 reflected in the onset and peak production of ethylene. Again, the stress generated by the



535 mechanical injuries could impact the oxidative status of the fruit, enhance cell membrane  
536 degradation and, as a consequence, reduce the potential fruit GL.

537         Several fungi at the post-harvest stage also have the potential to produce ethylene and  
538 therefore have a negative impact on fruit GL. The *in vitro* ethylene production capacity of  
539 *Colletotrichum musae*, the main agent causing banana anthracnose (De Lapeyre de Bellaire and  
540 Mourichon, 1997), was confirmed and explained by Daundasekera *et al.* (2003); Fukuda *et al.*  
541 (1993). In fact, it seems that the fungus has a dual effect: producing ethylene itself, but also  
542 acting as a stress factor and indirectly inducing ethylene biosynthesis in the plant (Bleecker and  
543 Kende, 2000). Daundasekera *et al.* (2003) suggests the ability of *C. musae* to use host banana  
544 tissue to provide substrates for ethylene production but, at this point, the relative contribution  
545 of pathogen-produced ethylene versus host system I and system II (autocatalytic) ethylene  
546 production in this pathogen-host relationship is not known and remains to be studied. The  
547 fungal and fruit peeling injury effect is worth discussing with regard to oxidative protein  
548 degradation and to the subsequent auto-catalytic fruit ripening process. Indeed, it can be  
549 suggested that any external peel aggression could be translated as stress factors, thereby  
550 triggering auto-catalytic ethylene synthesis and consequently resulting in reduced fruit GL  
551 potential.

552

## 553 5.2. *Hormonal compounds and gas treatment*

554

555         Auxins, kinins and gibberellins have been found to regulate aging processes in many  
556 plants, including fruits. Particularly, dipping whole banana fruit in gibberellic acid (GA<sub>3</sub>)  
557 solution was found to postpone the climacteric peak rise and therefore to extend GL (Archana  
558 and Sivachandiran, 2015; Osman and Abu-Goukh, 2008). A concentration of the dipping

559 solution at  $1.10^{-4}$  M was proved to increase GL from 13 (without GA<sub>3</sub>) to 18 d at 20 °C and  
560 under saturating RH conditions. It should, however, be pointed out that the concentration of  
561 GA<sub>3</sub> actually fixed in the tissue is not known, with peel and mainly cuticular wax acting as a  
562 hydrophobic barrier. Huang and Jiang (2012), using another plant growth regulator,  
563 forchlorfenuron (CPPU), increased by 2 d the GL of banana stored at 25 °C and at 75-95% RH.  
564 The combined effects of CPPU (phenylurea type molecule) and GA<sub>3</sub> were also studied by  
565 Huang *et al.* (2014). The most beneficial effect was obtained by dipping the fruits in a mixture  
566 composed of 10 mg.L<sup>-1</sup> of CPPU and 50 mg.L<sup>-1</sup> of GA<sub>3</sub>: The treatment delayed the occurrence  
567 of the peak of respiration but had a steady ethylene production rate at the green stage. The  
568 molecular mechanism was not known and is still to be proved.

569 Nitrous oxide (N<sub>2</sub>O), although not tested on banana but on other climacteric fruits  
570 (tomato, avocado), also blocks or delays ACC and ACO activity, and could be worth  
571 considering (Gouble *et al.*, 1995). N<sub>2</sub>O, which is an anaesthetic, is chemically neutral and non-  
572 toxic and therefore clearly differs from the very toxic but efficient ethylene oxide in extending  
573 GL (Williams *et al.*, 2003). As a consequence, autocatalytic ethylene evolution is inhibited and  
574 GL therefore extended. Again, although this treatment is promising, it should be considered  
575 with regard to food legislation, which does not accept this gas treatment for fruits and  
576 vegetables.

577

### 578 5.3. *1-Methylcyclopropene (1-MCP) treatment*

579

580 An exciting new strategy for controlling ethylene production, and thus fruit ripening and  
581 senescence, especially of climacteric fruits, as well as the senescence of vegetative tissues, has  
582 emerged with the discovery and commercialization of the inhibitor of ethylene perception, 1-

583 methylcyclopropene (1-MCP) (Jiang *et al.*, 2004; Watkins, 2006). 1-Methylcyclopropene is a  
584 cyclopropene derivative initially used as a synthetic plant growth regulator. It is structurally  
585 related to the natural plant hormone ethylene and is used commercially to slow down the  
586 ripening of fruit and to help maintain the freshness of cut flowers. The use of cyclopropenes to  
587 inhibit ethylene action was patented by Sisler and Blankenship (1996). Macnish *et al.* (2000)  
588 established an extension of the GL of bananas stored at 20 °C when treated with 15  $\mu\text{L.L}^{-1}$  1-  
589 MCP and subsequently exposed to ethylene. Jiang *et al.* (1999b) showed that exposure for 24  
590 h at 0.5 or 1  $\mu\text{L.L}^{-1}$  1-MCP at 20 °C extended GL from 16 to 31 d compared to control fruits.  
591 Jiang *et al.* (1999a) demonstrated that 1  $\mu\text{L.L}^{-1}$  1-MCP for 1 h at 20 °C delayed the ripening  
592 effects induced by 100  $\mu\text{L.L}^{-1}$  ethylene. Lastly, Golding *et al.* (1998) showed that the  
593 effectiveness of 1-MCP on banana fruit was closely related to its colour stage. A commercial  
594 breakthrough in 1-MCP application technology resulted from the formulation of 1-MCP as a  
595 stable powder in which it is complexed with  $\gamma$ -cyclodextrin, so that 1-MCP is easily released as  
596 a gas when the powder is dissolved in water (Edgington *et al.*, 2013; Zhang *et al.*, 2013).

597         Despite good results for 1-MCP delaying fruit softening (Bagnato *et al.*, 2003), soluble  
598 solid accumulation and colour development, an uneven ripening of peel following treatment  
599 with 1-MCP has been reported (De Martino *et al.*, 2007; Harris *et al.*, 2000). This uneven  
600 ripening of the peel appears when 1-MCP is applied after ethylene treatment to bananas that  
601 have not completely lost their green peel colour, and results in a dull-grey appearance.  
602 Moreover, these symptoms are often combined with areas on the peel that remain green, similar  
603 to blotchy ripening of tomatoes. It has been observed on banana fruit treated with ethylene at  
604 ripening stage 2, before or after 1-MCP treatment, that respiration was completely inhibited by  
605 1-MCP, whereas ethylene was slightly affected and this response affected the quality  
606 characteristics of bananas on a different level (DeMartino *et al.*, 2004). In particular, the  
607 occurrence of the yellow colour was completely delayed whenever the 1-MCP treatment was

608 carried out. Similar results, but with a lower response, were obtained when treating bananas  
609 with 1-MCP at a more advanced ripening stage.

610 It therefore clearly appears that using 1-MCP in the banana food chain will present many  
611 drawbacks in terms of logistical *vs.* quality improvement:

- 612 - Gassing fruit with 1-MCP at the green stage after harvesting at the production site  
613 causes some fruits, depending on their maturity on harvesting, to display severe  
614 visual defects (uneven green discoloration) when ripening is induced by ethylene  
615 after shipping, whatever the ethylene concentration and contact time (Feygenberg *et*  
616 *al.*, 2010).
- 617 - Gassing fruit with 1-MCP at colour stage 2 (light green) after ripening induction  
618 with ethylene is effective in greatly slowing down and even blocking fruit ripening.  
619 As the fruit cannot be consumed at this ripening stage, this option is not acceptable  
620 (DeMartino *et al.*, 2004).
- 621 - Gassing fruit with 1-MCP at colour stage 3-4 (green-yellow) after ripening  
622 induction with ethylene is not effective in slowing down ripening (DeMartino *et al.*,  
623 2004).

624 As a conclusion, since the effectiveness of 1-MCP varies with fruit maturity, and in any  
625 commercial consignments there is a mixture of fruit maturity, 1-MCP has limited commercial  
626 potential for the storage of unripe Cavendish bananas (Harris *et al.*, 2000). The study by Golding  
627 *et al.* (1998) confirmed that the application of 1-MCP significantly delayed and disrupted  
628 degreening, even when propylene was applied continuously, but that incomplete and uneven  
629 yellowing of the peel was a feature of fruit treated with 1-MCP fruit. Indeed, although yellowing  
630 is initiated by ethylene, completion of the process involves enzymes whose biosynthesis may  
631 be irreversibly disrupted by 1-MCP.

632

633 5.4. *Fruit coating and dipping*

634

635 Recently, increased efforts have been made to develop coatings using new preservative  
636 compounds that could generate a modified atmosphere by creating a semipermeable barrier  
637 against oxygen and carbon dioxide (Kudachikar *et al.*, 2011). Among them, Maqbool *et al.*  
638 (2011b) applied an edible coating composed of 10% gum Arabic plus 1% chitosan. Coated  
639 fruits had far fewer cracks, showed a smoother surface, and fruit GL was extended for up to 33  
640 d. This aqueous dispersion of sucrose esters of fatty acids, and the sodium salt of  
641 carboxymethylcellulose, indeed modifies the internal atmosphere of the fruit and delays the  
642 subsequent climacteric phase. Lastly, coating with Arabic gum was improved using 0.4%  
643 cinnamon oil (Maqbool *et al.*, 2011a). Indeed, by controlling *Colletotrichum Musae*, the main  
644 fungus encountered after the harvest on banana, these authors indirectly preserved potential  
645 banana GL (cf. § 5.1.). Basil oil was also shown to maintain banana GL by controlling fungal  
646 attacks that could develop during shipping (Anthony *et al.*, 2003; Siriwardana *et al.*, 2017).

647 As salicylic acid has been shown to affect the biosynthesis and action of ethylene, the  
648 effects of salicylic acid were explored (Srivastava and Dwivedi, 2000). By dipping the fruits in  
649 500  $\mu$ M of salicylic acid for 6 h, this compound acted as an ethylene antagonist and prolonged  
650 fruit GL by up to 3 d at 25 °C.

651 Lastly, although heat treatments (thermotherapy) have been used for over a century to  
652 free plant materials from pathogens, this post-harvest treatment of fruit could also be used to  
653 modify fruit responses to other stresses and maintain fruit quality during storage (Paull and  
654 Chen, 2000). The detrimental effect on final fruit quality was, however, not really highlighted

655 in these studies; heat treatment at more than 55 °C definitely *degrades* the subcellular cuticular  
656 wax layer and therefore increases peel browning at the ripening stage.

657

## 658 **6. GL optimization throughout the banana cold chain**

659

### 660 *6.1. Reefer, pallet box and carton levels scale*

661

662 Although palletized bananas have mainly been transported on dedicated vessels in the  
663 past, transportation is now shifting to containers on third-party vessels. While such  
664 transportation enables a more flexible reaction to fluctuating market volumes, shipping by third-  
665 party vessels in rented refrigerated containers (reefers) can cause more quality-related  
666 problems, unless adequate care is taken to maintain optimum transport conditions (Jedermann  
667 et al., 2014b).

668 Refrigerated containers, or "reefers", as they are regularly known, are of particular interest  
669 to shipping companies and similar organizations, because they permit relatively high freight  
670 rates and margins that are not possible with dry containers. The temperature settings of the  
671 reefer are prescribed in a range of 13 to 18 °C. In the case of goods with a high water content  
672 and 2<sup>nd</sup> order biotic activity (BA 2), such as fruit and vegetables in which respiration processes  
673 predominate, ventilation has not only to ensure that temperature and humidity requirements are  
674 met, but also gas exchanges. Ventilation ensures that the necessary oxygen is supplied and that  
675 harmful gases (carbon dioxide, ethylene) are removed.

676 The supply chain of the banana trade is a typical cold chain. The banana farm is the  
677 starting point of the banana cold chain, and the final customer is the end point (Figure 1 from  
678 Chen and Notteboom (2012)).

679 As bananas are exported over long distances, requiring days of sea shipment to reach the  
680 ripening location and thereafter the consumer location, fruit physiology and exogenous gas  
681 sensitivity need to be addressed jointly with the industrial chain and logistical requirements.  
682 Indeed, it takes between 5 and 35 d for bananas to reach the final customers, depending on the  
683 area considered. If any bananas ripen during transportation, they not only cannot be sold, but  
684 also endanger the whole container of bananas. Jedermann *et al.* (2013); Jedermann *et al.*  
685 (2014a); Jedermann *et al.* (2014b); Praeger *et al.* (2013) evaluated some of the suggested  
686 innovations integrating logistical food chain constraints. Ethylene management should be  
687 particularly discussed regarding the structure of the cold chain and integration of the  
688 “neighborhood” of each entity (cluster, carton, pallet box). Indeed, during shipping, each  
689 banana cluster cannot be individually considered, as there are other clusters in the same polybag  
690 that very probably come from another bunch and therefore have a different physiology and fruit  
691 maturity at harvest. This consideration can be scaled up to the carton or pallet box levels: each  
692 one impacting on and being impacted by its neighbors in terms of the temperature and gas  
693 composition of the surrounding atmosphere. Inside the box, the bananas are usually protected  
694 by a polyethylene bag to prevent dehydration. Indeed, post-harvest packaging of fruits in  
695 cartons lined with polyethylene film resulted in a longer GL (Elkashif *et al.*, 2010). The bag  
696 may either have some small holes to allow penetration of a controlled atmosphere (CA) into the  
697 box, provided by the ship, or may be completely sealed to generate a higher CO<sub>2</sub> concentration  
698 and lower O<sub>2</sub> concentration by respiration of the fruit.

699 Controlling the temperature, CO<sub>2</sub>, O<sub>2</sub> and ethylene concentrations at reefer, pallet box and  
700 carton levels is a real challenge and numerous studies and innovative technologies have been  
701 developed to achieve the required parameters to optimize banana GL.

702

## 703 6.2. *Modified Atmosphere Packaging (MAP)*

704

705 MAP is one of the most accepted methods for extending the shelf life of perishable and  
706 semi-perishable food products by altering the relative proportions of atmospheric gases  
707 surrounding the produce. However, the high capital cost of gas packaging machinery to control  
708 the atmosphere at the reefer scale has limited the use of this technology. This gives rise to the  
709 concept of active packaging (Sen *et al.*, 2012) Besides being independent of package  
710 permeability and gas packaging equipment, this packaging system is more rapid and accurate  
711 than traditional MAP. The concept of active packaging is one of the emerging technologies in  
712 food packaging. It has been defined as a system in which the product, the package and the  
713 environment interact in a positive way to extend GL or to achieve some characteristics that  
714 cannot be obtained otherwise (Miltz *et al.*, 1995). The active system can be an integral part of  
715 the package or be a separate component placed inside the package and different substances  
716 capable of either absorbing or releasing a specific gas control the atmosphere inside the  
717 package. Active packaging components can work as either an absorbing or releasing system.

718

## 719 6.3. *GL optimization at carton level*

720



721 Polyethylene bags are extensively proposed as a trigger, not only to protect fruits from  
722 external damage but also as a technology to delay ripening of bananas during storage and  
723 thereby increase GL. Commonly, potassium permanganate was added to these polyethylene  
724 bags as an ethylene absorbent to delay the potential GL even more. The most popular method  
725 at carton level is the oxidation of ethylene by potassium permanganate (KMnO<sub>4</sub>), adsorbed on  
726 an inert carrier with a large surface area, such as silica gel, alumina, and activated carbon. The  
727 stripping chemical mechanism is rather simple, as described here:  $3 \text{C}_2\text{H}_4 + 12 \text{KMnO}_4 \rightarrow 12$   
728  $\text{MnO}_2 + 12 \text{KOH} + 6 \text{CO}_2$ . Considering the low basal level of ethylene vs. the CO<sub>2</sub> (~ 1 ppm of  
729 ethylene / 4 % of CO<sub>2</sub>) concentration, the release of 2 moles of CO<sub>2</sub> for 1 mole of ethylene does  
730 not have a great impact on the controlled atmosphere composition (Mangaraj and Goswami,  
731 2009). Chamara et al. (2000) extended the GL of bananas cv. 'Kolikuttu' from 4 to 20 d at 25 °C  
732 and 85% RH by packing them in LDPE bags (75 µm) complemented with ethylene scavenger.  
733 Thus, GL could be greatly boosted using a modified atmosphere naturally obtained through the  
734 equilibrium between natural fruit respiration and PELD permeability and ethylene scavengers.  
735 Consequently, packing bananas as individual hands in LDPE (0.075 mm) bags with a 1:1  
736 surface to weight ratio (cm<sup>2</sup>.g<sup>-1</sup>) containing 50 mL of saturated potassium permanganate  
737 absorbed onto suitable porous matrices could be recommended to increase GL.

738 Passive modified atmosphere (2% O<sub>2</sub> and 5% CO<sub>2</sub>) packaging of bananas completed with  
739 an ethylene scrubber was found to increase fruit GL five-fold compared to fruits stored without  
740 wraps. Again, this gas composition is a result of the tryptic: fruit quantity/surface area of  
741 available film ratio, CO<sub>2</sub> exhausted at a given temperature, and gas permeability of the PEHD  
742 polybag. The combined effect of ethylene and CO<sub>2</sub> scrubber in the polyethylene bag during  
743 fruit shipping at 13 °C was tested by Chauhan *et al.* (2006). The increase in GL was only 2 d  
744 more using the two absorbers, while ethylene absorber alone led to an increase in GL from 8 to  
745 13 days. It appears that the concentration of ethylene surrounding the fruit is really the more

746 strategic parameter to be controlled during shipping until the initiation of the ripening stage, to  
747 ensure an optimized GL.

748 Another approach was using only material permeability to ensure the required atmosphere  
749 during shipping to maintain the potential GL. These materials included Banovac<sup>®</sup>, also called  
750 unvented polybag (Narayana *et al.*, 2002) which consists of 0.4 mm thick polyethylene bags in  
751 which the carbon dioxide content is raised to 5%, the oxygen content is reduced to 2%  
752 ("modified atmosphere"). The ethylene that arises is absorbed by adding potassium  
753 permanganate. However, Banovac<sup>®</sup> bags must be torn open before the ripening can be initiated,  
754 the high CO<sub>2</sub> concentration accumulating during ripening making this action necessary. The  
755 need to rip open the bags before gassing results in added labor costs.

756 In recent years, laser micro-perforation of the polybags has been the most promising  
757 technology to ensure a passive but steadily modified atmosphere. Indeed, these  
758 micro-perforations allow for the transmission of oxygen, CO<sub>2</sub> and ethylene gases into and out  
759 of the polybags (Varriano-Marston, 2008). Given the ethylene permeability of this wrap, this  
760 technology provides a package that does not have to be ripped open to initiate the ripening  
761 cycle. This approach was further optimized by Balasubramanian *et al.* (2013b), who provided  
762 a polymeric film, which comprised one or more copolymers of ethylene with a polar monomer,  
763 in which the oxygen transmission rate of the said wrap was 8,000 to 16,000 cm<sup>3</sup>.h<sup>-1</sup>. These  
764 perforated plastic bags could display non-uniform perforation density with the density of the  
765 lower zone being greater than that of the upper zone (Balasubramanian *et al.*, 2013a).

766

767 *6.4. Temperature and RH control at reefer level*

768

769 At the industrial level in the reefer, Jedermann et al. (2014b) found an exponential  
770 function for the relationship between storage temperature  $T$  and the average GL for the  
771 temperature range between  $T = 12\text{ }^{\circ}\text{C}$  and  $T = 30\text{ }^{\circ}\text{C}$ :  $GL(d) = 159.86 e^{-0.124 T}$  in normal air  
772 within a polyethylene bag at 98% RH. At an optimum storage temperature of  $13\text{ }^{\circ}\text{C}$ , the green  
773 life lasted about 30 d and for each  $10\text{ }^{\circ}\text{C}$  temperature increase, the green life was reduced by a  
774 factor of  $Q_{10} = 3.46$ . Green life decreased to one week at a storage temperature of  $25\text{ }^{\circ}\text{C}$ . The  
775 parameters of this equation should be modified depending on whether fruits are stored with or  
776 without  $\text{CO}_2$  control. Thus, it becomes  $GL(d) = 122.14 e^{-0.09 T}$  if the  $\text{CO}_2$  level reaches 5% or  
777 more, meaning the estimated fruit GL at  $15\text{ }^{\circ}\text{C}$  rises from 25 d to 32 d at 5%  $\text{CO}_2$  (Jedermann  
778 et al., 2013; Mees, 2017). Still at reefer level, Lang *et al.* (2011) proposed an interesting  
779 synthesis of the temperature, RH and  $\text{CO}_2$  effect on banana GL during sea exports from Latin  
780 America to Europe (Table 3).

781 While the high sensitivity of banana fruits to ethylene was shown at laboratory level  
782 (individual banana fingers or clusters), the management and optimization of GL at reefer level  
783 needs to consider all the key parameters as a whole. Indeed, and as an example, one 18 kg box  
784 of yellow bananas produces enough ethylene in 2.2 d to increase the concentration in the whole  
785 container with a free air volume of  $47.4\text{ m}^3$  to a critical threshold of 0.1 ppm, if the air flaps are  
786 closed, and no ethylene is released into the atmosphere (Jedermann et al., 2014b).

787 Controlling, optimizing and estimating the internal fruit temperature at reefer level is a  
788 real challenge. The speed of the cooling process depends largely on the quality and age of the  
789 cooling equipment, but surprisingly there is no preferred location for the hottest point inside the  
790 container (Jedermann et al., 2014b). As an example, after 8 d of shipping with a set-point fixed  
791 at  $13.9\text{ }^{\circ}\text{C}$ , the temperature difference could reach  $18\text{ }^{\circ}\text{C}$  in an old reefer while being only 14.5-  
792  $15\text{ }^{\circ}\text{C}$  in a new one. Cooling efficiency is therefore a key parameter that needs to be clearly  
793 defined. Furthermore, trucks or rail cars are frequently not refrigerated, so bananas only start

794 their cooling process once loaded into the vessel hatch. Cooling delays can range from 4 to 36  
795 h. This cooling delay is frequently considered one of the causes of premature ripening in transit.

796 Delays in cooling can have a marked influence on banana ripening during subsequent  
797 transit (Madrid, 1996). For fruit exposed to 12 h of cooling delay (30 °C instead of 14 °C, steady  
798 RH at 95%), the GL duration dropped by 12%, while GL was reduced by ~20% for fruit exposed  
799 to 24 h of cooling delay. Average shipment and delivery times from the tropics to the ripeners  
800 are around 18 – 20 days, so that losses of 4 to 6 days of green life can have a significant impact  
801 on the ‘ripe and turning’ incidence.

802 The Cargo Loss Prevention Information Handbook (Handbook, 2003) is very useful for  
803 knowing the temperature rise during banana transport if the cooler system of the reefer is  
804 damaged. As an example, 20 t of bananas that are temperature stabilized at 13 °C in a reefer  
805 will have their temperature reach 16.5 °C after only 48h. Given the impact of temperature rises  
806 on banana GL, this damage will undoubtedly provoke fruit ripening in the reefer, but also tend  
807 to increase the average temperature of the ship. To avoid such uneven ripening initiation, Haass  
808 *et al.* (2015) developed the so called “Intelligent Container”. This Intelligent Container is able  
809 to calculate the green life of its cargo and this leads to the feasibility of quality driven  
810 distribution. Thus, banana losses should be decreased and both transport costs and carbon  
811 emissions should be reduced even further. The use of chlorophyll fluorescence in fruit and  
812 vegetable storage (HarvestWatch<sup>TM</sup>) could be a good solution for optimizing the O<sub>2</sub>  
813 concentration in a dynamic controlled-atmosphere (DCA) (Prange *et al.*, 2012).

814

815 6.5. *GL optimization through innovative technology at reefer level*

816

817 Temperature-related problems are mainly caused by an imbalance between generated and  
818 removed heat. Jedermann et al. (2013) identified the width of the gaps between pallets as the  
819 major influence on the spatial temperature profile. The best cooling was achieved with a 4 cm  
820 wide gap between pallets and a gap from the wall, therefore meaning that optimized stowage  
821 of pallets is needed, but also that the reefer's wall should not be flat but present instead some  
822 regular notches. Although developed on citrus fruit, the study by Defraeye *et al.* (2015a) is  
823 worth discussing. The existence of gaps between the pallets led to significant airflow short-  
824 circuiting, which reduced the cooling rate at all box heights on the pallet, but it improved  
825 cooling uniformity between the boxes to some extent. Simulations showed that low airflow  
826 rates typical for refrigerated containers do not only induce slower fruit cooling, compared to  
827 Forced-Air Precooling (FAC) airflow rates, but also the cooling heterogeneity between  
828 different layers of boxes (in height) and between individual fruits in a single box is greater. In  
829 addition, the existence of gaps between pallets invokes airflow short-circuiting, leading to  
830 greatly reduced fruit cooling rates.

831 Optimized airflow circulation to reduce ethylene concentration inside and outside the box  
832 and thereby maintain banana GL is achieved with fan optimization at the polybag, box and  
833 pallet levels. Indeed, *i*) polyethylene bags should not have fewer than 4 pinholes ( $0.01 \text{ dm}^2 \cdot \text{m}^{-2}$ )  
834 <sup>2</sup>) for 20 kg of banana fruit; *ii*) boxes are provided with perforations to ensure proper flow of  
835 cooling air (perforation not less than 8% of the total area) and these boxes should be perfectly  
836 aligned to ensure airflow passage; *iii*) pallet stowage should be optimized. To optimize  
837 ventilation using carton perforations, Sanabria *et al.* (2003) improved the ventilation pattern by  
838 developing a shade box with the usual plurality of ventilation apertures, but with those apertures  
839 being in communication when cartons were regularly stowed, thereby advantageously  
840 improving airflow through an entire palletized load of containers.

841 As maintaining market quality is of vital importance for the success of the banana  
842 industry, it is necessary not only to cool the product, but to cool it as quickly as possible after  
843 harvest. Since the rate of respiration is influenced by temperature, precooling to remove the  
844 field heat before storage will reduce the respiration rate, hence deterioration will decline  
845 accordingly (Brosnan and Sun, 2001). The process of precooling is the removal of field heat,  
846 which arrests the deterioration process, so as to maintain a high level of quality that ensures  
847 customer satisfaction (Brosnan and Sun, 2001). Forced air cooling was developed to  
848 accommodate products requiring relatively rapid removal of field heat immediately after  
849 harvest. Forced air or pressure cooling is a modification of room cooling and is accomplished  
850 by exposing packages of produce to a higher air pressure on one side than on the other. This  
851 technique involves particular stacking patterns and the baffling of stacks, so that the cooling air  
852 is forced through (rather than around) the individual containers. Consequently, a relatively  
853 small pressure difference between the two sides of the containers exists, resulting in good air  
854 movement and excellent heat transfer, hence faster cooling.

855 The economic cost of this high-speed temperature reduction should however be pointed  
856 out. If it is essential that the heat load be removed quickly, whatever the cooling technique used.

857 A poorly ventilated, or worse still, unventilated container of bananas with rapid  
858 respiration rates can quickly change the atmosphere, reversing the normal levels of oxygen and  
859 carbon dioxide in less than 24 hours. New reefer containers are bottom-air delivery units, which  
860 means that air is constantly supplied from the bottom of the container through the T-bar floor.  
861 Cool air circulates through and around the cargo as it absorbs cargo heat. In order to remove  
862 the gas generated by respiration, thereby reducing ethylene concentration surrounding the fruit  
863 and maintaining GL up to 28 days, it is recommended that fresh air be exchanged from the  
864 outside to the inside at a rate of  $30 \text{ m}^3 \cdot \text{h}^{-1}$  for banana.

865           Although closely related to ventilation efficiency, dedicated reefers have been developed  
866 to specifically reduce exogenous ethylene. The main requirement during storage identified by  
867 the agrifood sector is ‘online’ monitoring of ethylene in the ppb range with low-cost devices in  
868 the storage chambers (Janssen *et al.*, 2014). Indeed, if gas sensing systems for CO<sub>2</sub> fruit  
869 monitoring in containers were already available, they would enable more reliable predictions  
870 of GL by measuring the ethylene concentration inside a container. The “intelligent” container  
871 developed by Lang *et al.* (2011) might be a solution to this challenge. The online control of  
872 ethylene, hence GL, seems to be such a challenge that Herdeman (1997) proposed bypassing  
873 this challenge by only reducing ethylene once the bananas were stabilized at the desired holding  
874 temperature.

875           Different methods of ethylene removal (ventilation, catalytic oxidation, photochemistry  
876 under UV–C light, and KMnO<sub>4</sub>) were evaluated (Lawton, 1991). As ambient levels in the sea  
877 transport environment rarely exceed 0.01 ppm, and as the best available method for the removal  
878 of ethylene has so far been ventilation with air, the costs and benefits of ethylene removal  
879 technologies are worth evaluating (Keller *et al.*, 2013). Compared with the other ethylene  
880 oxidation methods, the photocatalytic oxidation process can be considered as a very promising  
881 and reliable technology, combining the efficiency of catalytic oxidation with both low energy  
882 consumption and low heat load resulting from UV irradiance. Using TiO<sub>2</sub>, photocatalytic  
883 processes chemically oxidize organic compounds into carbon dioxide and water at near-ambient  
884 temperatures to complete mineralization. It has proven to be an efficient method for removing  
885 ethylene from horticultural storage facilities in order to extend the postharvest storability of  
886 produce, and can further be used in combination with other means, such as cold storage,  
887 controlled atmospheres, or modified atmosphere packaging (Keller *et al.*, 2013). Since  
888 photocatalytic material is not consumed during the oxidation process, there is no need for the

889 replacement and disposal of depleted treatment units. It can be applied to both large and small-  
890 scale storage units and used for low and high ethylene concentrations.

891

## 892 **7. Conclusion**

893

894 This review definitely brought out the need to manage GL as a whole, meaning that from  
895 the orchard to unripe banana delivery after shipping, many preventive actions should be taken  
896 and optimized parameters observed. Indeed, the auto-induced climacteric peak could be  
897 considered as an internal physiological factor mainly dependent on cultural practices when  
898 external conditions modulate these ripening mechanisms.

899 Table 4 proposes several recommendations and correlated banana chain good practices to  
900 ensure optimum GL in the orchard, packing-house and reefer. While not exhaustive, this table  
901 tries to clearly depict the key parameters and how they should be managed. To be really  
902 effective in optimising fruit GL, these “good practices” should all be adopted totally, in order  
903 to achieve a synergetic effect up to ripening induction by exogenous ethylene in the ripening  
904 room.

905 For these best practices to be applicable to all other regions, good control of both Black  
906 Sigatoka and harvesting points is required in any event, whatever the country of origin and the  
907 context. Post-harvest technologies should be considered as a trigger and not as a ready-to-apply  
908 solution.

909 As an overall perspective for the future, it would seem that an integrated approach is  
910 needed, considering GL as the challenge. Indeed, whatever the production area and the transit



911 time, a continuum between producers, post-harvest methods and shipping arrangements will be  
912 necessary to counteract how Black Sigatoka affects GL.

913 As technologies evolve, stakeholders will be able to pilot the post-harvest life of the fruit  
914 using intelligent containers that would adapt the composition of the atmosphere and the  
915 temperature to the cargo. In any event, research is required to try and estimate fruit GL after  
916 harvest as accurately as possible, using spectral and non-invasive technologies for instance.  
917 This will considerably change all our approaches to GL optimization and will considerably  
918 reduce fruit losses after shipping.

919

920

921

922

923

924 **References**

925

926 Anthony, S., Abeywickrama, K., Wijeratnam, S.W., 2003. The effect of spraying essential oils of  
927 *Cymbopogon nardus*, *Cymbopogon flexuosus* and *Ocimum basilicum* on postharvest diseases and  
928 storage life of Embul banana. *The Journal of Horticultural Science and Biotechnology* 78, 780-785.

929 Archana, U., Sivachandiran, S., 2015. Effect of application of gibberellic acid (GA3) on shelf-life of  
930 banana. *International Journal of Research in Agriculture and Food Sciences* 3, 2311-2476.

931 Areas, J.A., Garcia, E., Lajolo, F.M., 1988. Effect of protein synthesis inhibitors on the climacteric of  
932 banana (*Musa acuminata*). *Journal of Food Biochemistry* 12, 51-60.

933 Bagnato, N., Barrett, R., Sedgley, M., Klieber, A., 2003. The effects on the quality of Cavendish  
934 bananas, which have been treated with ethylene, of exposure to 1-methylcyclopropene.

935 *International journal of food science & technology* 38, 745-750.

936 Blake, J., Peacock, B., 1971. Effect of temperature on the preclimacteric life of bananas. *Queensland  
937 journal of Agricultural and Animal Sciences*.

938 Bleecker, A.B., Kende, H., 2000. Ethylene: a gaseous signal molecule in plants. *Annual Review of Cell  
939 and Developmental Biology* 16, 1-18.

940 Bufler, G., 1986. Ethylene-promoted conversion of 1-aminocyclopropane-1-carboxylic acid to  
941 ethylene in peel of apple at various stages of fruit development. *Plant Physiology* 80, 539-543.

942 Bugaud, C., Chillet, M., Beauté, M.P., Dubois, C., 2006. Physicochemical analysis of mountain bananas  
943 from the French West Indies. *Scientia Horticulturae* 108, 167-172.

944 Bugaud, C., Daribo, M.O., Dubois, C., 2007. Climatic conditions affect the texture and colour of  
945 Cavendish bananas (Grande Naine cultivar). *Scientia Horticulturae* 113, 238-243.

946 Burdon, J., Dori, S., Lomaniec, E., Marinansky, R., Pesis, E., 1994. The post-harvest ripening of water  
947 stressed banana fruits. *Journal of Horticultural Science* 69, 799-804.

948 Castelan, F.P., Abadie, C., Hubert, O., Chilin-Charles, Y., de Bellaire, L.d.L., Chillet, M., 2013. Relation  
949 between the severity of Sigatoka disease and banana quality characterized by pomological traits and  
950 fruit green life. *Crop protection* 50, 61-65.

951 Castelan, F.P., Saraiva, L., Lange, F., de Bellaire, L.d.L., Cordenunsi, B.R., Chillet, M., 2012. Effects of  
952 black leaf streak disease and sigatoka disease on fruit quality and maturation process of bananas  
953 produced in the subtropical conditions of southern Brazil. *Crop Protection* 35, 127-131.

954 Chamara, D., Illeperuma, K., Galappatty, T., Sarananda, K., 2000. Modified atmosphere packaging of  
955 'Kolikuttu'bananas at low temperature. *The Journal of Horticultural Science and Biotechnology* 75,  
956 92-96.

957 Chang, W.H., Hwang, Y.J., 1990. Effect of ethylene treatment on the ripening, polypyphenoloxidase  
958 activity and water-soluble tannin content of Taiwan Northern banana at different maturity stages  
959 and the stability of banana polyphenoloxidase. *Acta Horticulturae* 275.

960 Chen, L., Notteboom, T., 2012. Distribution and value added logistics in the cold chain product  
961 market with application to the role of seaports, *Asian Logistics Round Table 2012 Conference (ALRT  
962 2012)*, University of British Columbia (UBC), Vancouver, 14-15 June 2012.

963 Chillet, M., Abadie, C., Hubert, O., Chilin-Charles, Y., de Bellaire, L.d.L., 2009. Sigatoka disease reduces  
964 the greenlife of bananas. *Crop Protection* 28, 41-45.

965 Chillet, M., Castelan, F.P., Abadie, C., Hubert, O., de Bellaire, L.d.L., 2013. Necrotic leaf removal, a key  
966 component of integrated management of *Mycosphaerella* leaf spot diseases to improve the quality of  
967 banana: the case of Sigatoka disease. *Fruits* 68, 271-277.

968 Chillet, M., de Lapeyre de Bellaire, L., Hubert, O., 2008. Measurement of banana green life. *Fruits* 63,  
969 125-127.

970 Chillet, M., Hubert, O., Rives, M.J., de Bellaire, L.d.L., 2006. Effects of the physiological age of bananas  
971 on their susceptibility to wound anthracnose due to *Colletotrichum musae*. *Plant Disease* 90, 1181-  
972 1185.

973 Chuc-Uc, J., Brito-Argáez, L., Canto-Canché, B., Tzec-Simá, M., Rodríguez-García, C., Peraza-

974 Echeverría, L., Peraza-Echeverría, S., James-Kay, A., Cruz-Cruz, C.A., Peña-Rodríguez, L.M., 2011. The

975 in vitro secretome of *Mycosphaerella fijiensis* induces cell death in banana leaves. *Plant Physiology*  
976 and *Biochemistry* 49, 572-578.

977 Daniells, J., Lisle, A., Bryde, N., 1994. Effect of bunch trimming and leaf removal at flowering on  
978 maturity bronzing, yield, and other aspects of fruit quality of bananas in North Queensland.  
979 *Australian Journal of Experimental Agriculture* 34, 259-265.

980 Daundasekera, M., Joyce, D., Aked, J., Adikaram, N., 2003. Ethylene production by *Colletotrichum*  
981 *musae* in vitro. *Physiological and Molecular Plant Pathology* 62, 21-28.

982 De Lapeyre de Bellaire, L., Fouré, E., Abadie, C., Carlier, J., 2010. Black Leaf Streak Disease is  
983 challenging the banana industry. *Fruits* 65, 327-342.

984 De Lapeyre de Bellaire, L., Mourichon, X., 1997. The biology of *Colletotrichum musae* (Berk. et Curt.)  
985 Arx and its relation to control of banana anthracnose, II International Symposium on Banana: I  
986 International Symposium on Banana in the Subtropics 490, pp. 297-304.

987 De Martino, G., Mencarelli, F., Golding, J.B., 2007. Preliminary investigation into the uneven ripening  
988 of banana (*Musa sp.*) peel. *New Zealand Journal of Crop and Horticultural Science* 35, 193-199.

989 Defraeye, T., Cronjé, P., Berry, T., Opara, U.L., East, A., Hertog, M., Verboven, P., Nicolai, B., 2015.  
990 Towards integrated performance evaluation of future packaging for fresh produce in the cold chain.  
991 *Trends in Food Science and Technology* 44, 201-225.

992 DeMartino, G., Mincini, M., Forniti, R., Botondi, R., Bellincontro, A., Mencarelli, F., 2004. Ethylene  
993 depending and non-depending metabolisms during postharvest banana ripening, III International  
994 Symposium on Tropical and Subtropical Fruits 864, pp. 275-282.

995 Dominguez, M., Vendrell, M., 1993. Ethylene biosynthesis in banana fruit: evolution of EFE activity  
996 and ACC levels in peel and pulp during ripening. *Journal of Horticultural Science* 68, 63-70.

997 Edgington, T.B., Malefyt, T., Ureña-Padilla, A.R., 2013. Banana treatments. Google Patents.

998 El Hadrami, A., Kone, D., Lepoivre, P., 2005. Effect of juglone on active oxygen species and  
999 antioxidant enzymes in susceptible and partially resistant banana cultivars to black leaf streak  
1000 disease. *Eur J Plant Pathol* 113, 241-254.

1001 Fan, X., Mattheis, J.P., Fellman, J.K., 1998. A role for jasmonates in climacteric fruit ripening. *Planta*  
1002 204, 444-449.

1003 Ferris, R., Hotsonyame, G., Wainwright, H., Thompson, A., 1993. The effects of genotype, damage,  
1004 maturity, and environmental conditions on the postharvest life of plantain. *Tropical Agriculture*  
1005 London Than Trinidad 70, 45-45.

1006 Feygenberg, O., Ben-Arie, R., Pesis, E., 2010. Postharvest Application of 1-MCP to Green or Yellow  
1007 Banana for Extending Storability and Shelf-Life, VI International Symposium on Banana: XXVIII  
1008 International Horticultural Congress on Science and Horticulture for People 928, pp. 219-225.

1009 Finger, F.L., Puschmann, R., Raimundo, S.B., 1995. Effects of water loss on respiration, ethylene  
1010 production and ripening of banana fruit. *Revista Brasileira de Fisiologia Vegetal* 7, 115-118.

1011 Fukuda, H., Ogawa, T., Tanase, S., 1993. Ethylene production by micro-organisms. *Advances in*  
1012 *Microbial Physiology* 35, 275-306.

1013 Ganry, J., Chillet, M., 2008. Methodology to forecast the harvest date of banana bunches. *Fruits* 63,  
1014 371-373.

1015 Ganry, J., Meyer, J., 1975. Recherche d'une loi d'action de la temperature sur la croissance des fruits  
1016 du bananier. *Fruits*.

1017 Gao, J.P., Kubo, Y., Nakamura, R., Inaba, A., 1990. Induction of ethylene biosynthesis in banana fruit  
1018 under different ripening conditions. *Journal of the Japanese Society for Horticultural Science* 59, 665-  
1019 671.

1020 Golding, J., Shearer, D., Wyllie, S., McGlasson, W., 1998. Application of 1-MCP and propylene to  
1021 identify ethylene-dependent ripening processes in mature banana fruit. *Postharvest Biology and*  
1022 *Technology* 14, 87-98.

1023 Gonge, A., Patel, N., Ahlawat, T., Patil, S., 2013. Effect of maturity and storage temperature on shelf-  
1024 life and quality of banana cv. Grand Naine. *Journal of Horticultural Science* 8, 95-98.

1025 Gouble, B., Fath, D., Soudain, P., 1995. Nitrous oxide inhibition of ethylene production in ripening and  
1026 senescing climacteric fruits. *Postharvest Biology and Technology* 5, 311-321.

1027 Guillermet, C., Le Guen, R., Lescot, T., Dorel, M., De Lapeyre de Bellaire, L., 2016. Experimental  
1028 approaches for agroecological management of black leaf streak in dry and humid tropical conditions  
1029 Proceedings of the X International Symposium on Banana, ISHS Promusa Symposium on  
1030 Agroecological approaches to promote innovative banana production systems, Montpellier.  
1031 Hailu, M., Workneh, T.S., Belew, D., 2013. Review on postharvest technology of banana fruit. African  
1032 Journal of Biotechnology 12, 635-647.  
1033 Harris, D., Seberry, J., Wills, R., Spohr, L., 2000. Effect of fruit maturity on efficiency of 1-  
1034 methylcyclopropene to delay the ripening of bananas. Postharvest Biology and Technology 20, 303-  
1035 308.  
1036 Herdeman, R.W., 1997. Process for shipping and ripening fruits and vegetables. Google Patents.  
1037 Huang, H., Jiang, Y., 2012. Effect of plant growth regulators on banana fruit and broccoli during  
1038 storage. Scientia Horticulturae 145, 62-67.  
1039 Huang, H., Jing, G., Wang, H., Duan, X., Qu, H., Jiang, Y., 2014. The combined effects of phenylurea  
1040 and gibberellins on quality maintenance and shelf life extension of banana fruit during storage.  
1041 Scientia Horticulturae 167, 36-42.  
1042 Inaba, A., Nakamura, R., 1988. Numerical expression for estimating the minimum ethylene exposure  
1043 time necessary to induce ripening in banana fruit. Journal of the American Society for Horticultural  
1044 Science 113, 561-564.  
1045 Jackman, R., Yada, R., Marangoni, A., Parkin, K., Stanley, D., 1988. Chilling injury. A review of quality  
1046 aspects. Journal of food quality 11, 253-278.  
1047 Jedermann, R., Geyer, M., Praeger, U., Lang, W., 2013. Sea transport of bananas in containers–  
1048 Parameter identification for a temperature model. Journal of Food Engineering 115, 330-338.  
1049 Jedermann, R., Nicometo, M., Uysal, I., Lang, W., 2014a. Reducing food losses by intelligent food  
1050 logistics. The Royal Society.  
1051 Jedermann, R., Praeger, U., Geyer, M., Lang, W., 2014b. Remote quality monitoring in the banana  
1052 chain. Philosophical Transactions of the Royal Society of London A: Mathematical, Physical and  
1053 Engineering Sciences 372, 20130303.  
1054 Jiang, W., Zhang, M., He, J., Zhou, L., 2004. Regulation of 1-MCP-treated banana fruit quality by  
1055 exogenous ethylene and temperature. Food Science and Technology International 10, 15-20.  
1056 Jiang, Y., Joyce, D.C., Macnish, A.J., 1999a. Extension of the shelf life of banana fruit by 1-  
1057 methylcyclopropene in combination with polyethylene bags. Postharvest Biology and Technology 16,  
1058 187-193.  
1059 Jiang, Y., Joyce, D.C., Macnish, A.J., 1999b. Responses of banana fruit to treatment with 1-  
1060 methylcyclopropene. Plant Growth Regul 28, 77-82.  
1061 Joas, J., 1987. Quelques observations à propos du circuit de distribution de la banane antillaise (cv.  
1062 Cavendish) et des principaux facteurs définissant la qualité du fruit. Fruits 42, 493-504.  
1063 Johns, G., Scott, K., 1989a. Delayed harvesting of bananas with 'sealed' covers on bunches. 1. Modified  
1064 atmosphere and microclimate inside sealed covers. Australian Journal of Experimental Agriculture  
1065 29, 719-726.  
1066 Johns, G., Scott, K., 1989b. Delayed harvesting of bananas with 'sealed' covers on bunches. 2. Effect on  
1067 fruit yield and quality. Australian Journal of Experimental Agriculture 29, 727-733.  
1068 Jullien, A., Chillet, M., Malézieux, E., 2008. Pre-harvest growth and development, measured as  
1069 accumulated degree days, determine the post-harvest green life of banana fruit. The Journal of  
1070 Horticultural Science and Biotechnology 83, 506-512.  
1071 Jullien, A., Malézieux, E., Michaux-Ferrière, N., Chillet, M., Ney, B., 2001. Within-bunch variability in  
1072 banana fruit weight: importance of developmental lag between fruits. Annals of Botany 87, 101-108.  
1073 Kende, H., 1993. Ethylene biosynthesis. Annual review of plant biology 44, 283-307.  
1074 Kimani, E., Mathooko, F.s., Kahangi, E., Muchui, M., Njoroge, C., Onyango, C., 2017. Effect of  
1075 perforated blue polyethylene bunch covers on selected postharvest quality parameters of  
1076 tissuecultured bananas (*Musa* spp.) cv. Williams in Central Kenya.

1077 Kudachikar, V., Kulkarni, S., Prakash, M.K., 2011. Effect of modified atmosphere packaging on quality  
1078 and shelf life of 'Robusta' banana (*Musa sp.*) stored at low temperature. *Journal of food science and*  
1079 *technology* 48, 319-324.

1080 Lassoudière, A., 2007. *Le bananier et sa culture*. Editions Quae.

1081 Li, W., Huang, B., 1988. Studies on ethylene production and respiration rate in relation to other  
1082 ripening changes of three banana cultivars. *Acta Horticulturae Sinica* 15, 18-22.

1083 Littmann, M., 1972. Effect of water loss on the ripening of climacteric fruits. 29, 131-136.

1084 Macnish, A., Hofman, P., Joyce, D., Simons, D., Reid, M., 2000. 1-Methylcyclopropene treatment  
1085 efficacy in preventing ethylene perception in banana fruit and grevillea and waxflower flowers.  
1086 *Australian Journal of Experimental Agriculture* 40, 471-481.

1087 Madrid, M., 1996. Cooling delays and their impact on green life of bananas, *International Postharvest*  
1088 *Science Conference Postharvest* 96 464, pp. 513-513.

1089 Mahmoud, H., Elkashif, M., 2003. Evaluation of plant crop of introduced banana clones and the  
1090 effects of packaging on fruit quality. *Gezira Journal of Agricultural Science (Sudan)*.

1091 Maqbool, M., Ali, A., Alderson, P.G., Mohamed, M.T.M., Siddiqui, Y., Zahid, N., 2011a. Postharvest  
1092 application of gum arabic and essential oils for controlling anthracnose and quality of banana and  
1093 papaya during cold storage. *Postharvest Biology and Technology* 62, 71-76.

1094 Maqbool, M., Ali, A., Alderson, P.G., Zahid, N., Siddiqui, Y., 2011b. Effect of a Novel Edible Composite  
1095 Coating Based on Gum Arabic and Chitosan on Biochemical and Physiological Responses of Banana  
1096 Fruits during Cold Storage. *Journal of Agricultural and Food Chemistry* 59, 5474-5482.

1097 Marin, D.H., Blankenship, S.M., Sutton, T.B., Swallow, W.H., 1996. Physiological and chemical changes  
1098 during ripening of Costa Rican bananas harvested in different seasons. *Journal of the American*  
1099 *Society for Horticultural Science* 121, 1157-1161.

1100 Mees, H.O., 2017. Controlled reefers in the banana supply chain: energy reduction and quality  
1101 preservation. *Transport Engineering & Logistics*. TU Delft. Netherlands., Graduation Thesis for  
1102 master.

1103 Osman, H.E., Abu-Goukh, A., 2008. Effect of polyethylene film lining and gibberellic acid on quality  
1104 and shelf-life of banana fruits. *University of Khartoum Journal of Agricultural Sciences* 16, 242-261.

1105 Paull, R.E., Chen, N.J., 2000. Heat treatment and fruit ripening. *Postharvest Biology and Technology*  
1106 21, 21-37.

1107 Peacock, B., 1972. Effect of light on initiation of fruit ripening. *Nature* 235, 62-63.

1108 Peacock, B., Blake, J., 1970. Some effects of non-damaging temperatures on the Ufe and respiratory  
1109 behaviour of bananas. *Queensland Journal of Agricultural and Animal Sciences* 27, 147-168.

1110 Praeger, U., Linke, M., Jedermann, R., Moehrke, A., Geyer, M., BVBA, D.E.I., 2013. Effect of storage  
1111 climate on green-life duration of bananas, 5th International Workshop Cold Chain Management,  
1112 Bonn, Germany, University Bonn.

1113 Prasanna, V., Prabha, T., Tharanathan, R., 2007. Fruit ripening phenomena—an overview. *Critical*  
1114 *Reviews in Food Science and Nutrition* 47, 1-19.

1115 Purgatto, E., Oliveira do Nascimento, J.R., Lajolo, F.M., Cordenunsi, B.R., 2002. The onset of starch  
1116 degradation during banana ripening is concomitant to changes in the content of free and conjugated  
1117 forms of indole-3-acetic acid. *Journal of Plant Physiology* 159, 1105-1111.

1118 Ramírez, M., Sáenz, M.V., Vargas, A., Araya, M., 2008. Leaf pruning intensities at flowering of banana  
1119 (*Musa AAA*, cv. Grande Naine) did not influence fruit green and yellow life and quality. *Scientia*  
1120 *Horticulturae* 115, 319-322.

1121 Ramsey, M., Daniells, J., Anderson, V., 1990. Effects of Sigatoka leaf spot (*Mycosphaerella musicola*  
1122 Leach) on fruit yields, field ripening and greenlife of bananas in North Queensland. *Scientia*  
1123 *Horticulturae* 41, 305-313.

1124 Richardson, A.D., Duigan, S.P., Berlyn, G.P., 2002. An evaluation of noninvasive methods to estimate  
1125 foliar chlorophyll content. *New Phytologist* 153, 185-194.

1126 Robinson, J., 1996. *Bananas and plantains, crop production science in horticulture* 5. CAB  
1127 International, Wallingford.

1128 Robinson, J., Anderson, T., Eckstein, K., 1992. The influence of functional leaf removal at flower  
1129 emergence on components of yield and photosynthetic compensation in banana. *Journal of*  
1130 *Horticultural Science* 67, 403-410.

1131 Rodríguez-Bermejo, J., Barreiro, P., Robla, J.I., Ruiz-García, L., 2007. Thermal study of a transport  
1132 container. *Journal of Food Engineering* 80, 517-527.

1133 Santana Llado, J., Marrero Dominguez, A., 1997. The effects of peel abrasion on the postharvest  
1134 physiology and commercial life of banana fruits, II International Symposium on Banana: I  
1135 International Symposium on Banana in the Subtropics 490, pp. 547-554.

1136 Santosh, D., Tiwari, K., Reddy, R.G., 2017. Banana bunch covers for quality banana production—a  
1137 review. *Int J Curr Microbiol Appl Sci* 6, 1275-1291.

1138 Saraiva, L.d.A., Castelan, F.P., Shitakubo, R., Hassimotto, N.M.A., Purgatto, E., Chillet, M., Cordenunsi,  
1139 B.R., 2013. Black leaf streak disease affects starch metabolism in banana fruit. *Journal of Agricultural*  
1140 *and Food Chemistry* 61, 5582-5589.

1141 Sinha, A., Jawandha, S., Gill, P., Singh, H., 2019. Influence of pre-harvest sprays of calcium nitrate on  
1142 storability and quality attributes of plum fruits. *Journal of food science and technology* 56, 1427-  
1143 1437.

1144 Siriwardana, H., Abeywickrama, K., Kannangara, S., Jayawardena, B., Attanayake, S., 2017. Basil oil  
1145 plus aluminium sulfate and modified atmosphere packaging controls Crown rot disease in Embul  
1146 banana (*Musa acuminata*, AAB) during cold storage. *Scientia Horticulturae* 217, 84-91.

1147 Sisler, E., Blankenship, S., 1996. Patent No. 5,518,988. Method of counteracting an ethylene response  
1148 in plants 21.

1149 Sisler, E.C., Wood, C., 1988. Interaction of ethylene and CO<sub>2</sub>. *Physiologia Plantarum* 73, 440-444.

1150 Srikul, S., Turner, D., 1995. High N supply and soil water deficits change the rate of fruit growth of  
1151 bananas (cv. "Williams") and promote tendency to ripen. *Scientia Horticulturae* 62, 165-174.

1152 Srivastava, M.K., Dwivedi, U.N., 2000. Delayed ripening of banana fruit by salicylic acid. *Plant Science*  
1153 158, 87-96.

1154 Stewart, O.J., Raghavan, G., Golden, K.D., Gariépy, Y., 2005. MA storage of Cavendish bananas using  
1155 silicone membrane and diffusion channel systems. *Postharvest Biology and Technology* 35, 309-317.

1156 Thompson, A., 2011. *Banana (Musa spp.)*, *Postharvest Biology and Technology of Tropical and*  
1157 *Subtropical Fruits: Açai to Citrus*. Elsevier, pp. 216-244e.

1158 Tixier, P., Bugaud, C., Duguet, R., Salmon, F., 2010. Effect of preharvest and postharvest application  
1159 of calcium on banana green-life. *Fruits* 65, 201-208.

1160 Turner, D.W., Fortescue, J.A., 2012. *Bananas (Musa spp.)*. *Crop Post-Harvest: Science and*  
1161 *Technology, Perishables* 3, 24.

1162 Umber, M., Paget, B., Hubert, O., Salas, I., Salmon, F., Jenny, C., Chillet, M., Bugaud, C., 2011.  
1163 Application of thermal sums concept to estimate the time to harvest new banana hybrids for export.  
1164 *Scientia Horticulturae* 129, 52-57.

1165 Wade, N., Graham, D., 1987. A model to describe the modified atmospheres developed during the  
1166 storage of fruit in plastic films. *ASEAN Food Journal* 3, 105-111.

1167 Watkins, C.B., 2006. The use of 1-methylcyclopropene (1-MCP) on fruits and vegetables.  
1168 *Biotechnology Advances* 24, 389-409.

1169 Williams, O.J., Raghavan, G.S.V., Golden, K.D., Gariépy, Y., 2003. Postharvest storage of Giant  
1170 Cavendish bananas using ethylene oxide and sulphur dioxide. *Journal of the Science of Food and*  
1171 *Agriculture* 83, 180-186.

1172 Wills, R., Harris, D., Seberry, J., 1999. Delayed ripening of bananas through minimization of ethylene.  
1173 *Tropical agriculture* 76, 279-282.

1174 Wills, R., Warton, M., Mussa, D., Chew, L., 2001. Ripening of climacteric fruits initiated at low  
1175 ethylene levels. *Australian Journal of Experimental Agriculture* 41, 89-92.

1176 Wills, R.B., Golding, J.B., 2015. Reduction of energy usage in postharvest horticulture through  
1177 management of ethylene. *Journal of the Science of Food and Agriculture* 95, 1379-1384.

- 1178 Wills, R.B.H., Harris, D.R., Spohr, L.J., Golding, J.B., 2014. Reduction of energy usage during storage  
1179 and transport of bananas by management of exogenous ethylene levels. *Postharvest Biology and*  
1180 *Technology* 89, 7-10.
- 1181 Zhang, S., Becker, C.G., Yan, Y., Shi, Y., Chen, Y., Kalantar, T.H., Zhen, Y., Yang, X.G., Tucker, C.J., 2013.  
1182 Suspension of particles comprising cyclopropene complexes dispersed in a resin matrix. *Google*  
1183 *Patents*.
- 1184 Zude, M., Sasse, J., Schallnus, H., 2009. Non-invasive sensing of fruit development in banana and  
1185 papaya by means of a spectroscopic approach, *International Symposium Postharvest Pacifica 2009-*  
1186 *Pathways to Quality: V International Symposium on Managing Quality in 880*, pp. 277-281.

1187

1188

1189 **TABLE 1.** Effect of maturity and storage temperature on banana green life (d) (cv. Grande  
1190 naine) (taken from Gonge et al. (2013)).

<b>Level of maturity</b>	<b>Storage T °C</b>			<b>Mean green life (d)</b>
	<i>12 °C</i>	<i>14 °C</i>	<i>16 °C</i>	
75%	35	28	21	28
90%	29	24	16	23
100%	26	21	14	20

1191

1192

1193



1194

1195 **TABLE 2.** Regression equations of estimated green life (GL) duration (d) according to the range of temperatures and  
 1196 the CO<sub>2</sub> concentration.

Regression equations	Reference	Estimated	Estimated	Limiting conditions
		GL at 13 °C	GL at 15 °C	
GL (d) = [- 0.97 x T °F] + 93	Peacock and Blake (1970)	40	36	13 < T °C < 22 Normal air
GL (d) = 10 <sup>[-(0.02529 x T °F) + 2.898]</sup>	Blake and Peacock (1971)	32	25	15.5 < T °C < 35.5 Normal air
GL (d) = 159.86 e <sup>-0.124 T °C</sup>	Jedermann et al. (2014b)	32	25	12 < T °C < 30 Normal air
GL (d) = 122.14 e <sup>-0.09 T °C</sup>	Mees (2017)	38	32	12 < T °C < 30 CO <sub>2</sub> > 5%

1197

1198

1199 **TABLE 3.** Green life<sup>a</sup> of Cavendish bananas harvested in spring 2012 and stored under  
1200 different relative humidity (RH), T °C, and CO<sub>2</sub> concentration conditions (taken from  
1201 Jedermann et al. (2014b)).

<b>RH</b>	<b>Effect of RH</b>			<b>Effect of elevated CO<sub>2</sub></b>	
	<b>50-60%</b> <b>normal air</b>	<b>80%</b> <b>normal air</b>	<b>98%,</b> <b>&lt; 2% CO<sub>2</sub></b>	<b>98%,</b> <b>&lt; 2% CO<sub>2</sub></b>	<b>98%,</b> <b>5% CO<sub>2</sub></b>
T 15 °C	42 ± 4	37 ± 5	48 ± 2	57 ± 1	<b>61 ± 2</b>
T 18 °C	<b>23 ± 7</b>	28 ± 4	32 ± 2	30 ± 4	49 ± 17

1202 <sup>a</sup>only hand-top position GL is presented.

1203

1204

1205

1206

1207

1208

1209 **TABLE 4.** Summary of recommendations and correlated banana chain good practices to ensure optimum green life at the orchard, packing-house  
1210 and reefer levels of intervention.

<b>Levels of intervention</b>	<b>Recommendations(s)</b>	<b>Good practice(s) to set up</b>	<b>Key publication(s)</b>
<b>At orchard level</b>	Limit stress induced by fertilization and drought (when harvest at a specific fruit size/grade)	Low soil N supply and no soil water deficiency	Srikul and Turner (1995)
	Control of Sigatoka diseases	Elimination of necrotic parts of the leaves	Chillet et al. (2013)
	Optimisation of the harvest point: compromise yield and GL	Harvest stage at $900 \pm 50$ dd	Ganry and Chillet (2008)
<b>At packing house level</b>	Avoid peel abrasion after harvest	Do not injure the fruits during de-handing and cluster fruit preparation steps	Santana Llado and Marrero Dominguez (1997)

Control fungal attack	Use natural or chemical treatments that prevent or limit <i>Colletotrichum Musae</i> during shipping	Daundasekera et al. (2003)
Limit ethylene exhausting as much as possible	If possible, pre-cool fruit immediately after harvest	Defraeye <i>et al.</i> (2015)
	Limit cooling delay (< 4 h)	Madrid (1996) Herdeman (1997)
Reduce ethylene accumulation + Control the temperature at 13.5 ± 0.5 °C	Optimise ventilation at pallet and reefer level	Jedermann et al. (2014b) Jedermann <i>et al.</i> (2013)
	Shade storing of the reefers	Rodríguez-Bermejo <i>et al.</i> (2007)
Limit water loss	Maintain RH > 95-98%	Jedermann et al. (2014b)
<b>At ripening room level</b>	Avoid heterogeneous ripening induced by “ethylene pollution”	Proceed to the ripening step without delay Jedermann <i>et al.</i> (2014a)

1212 **Itemized list of Figures:**

1213

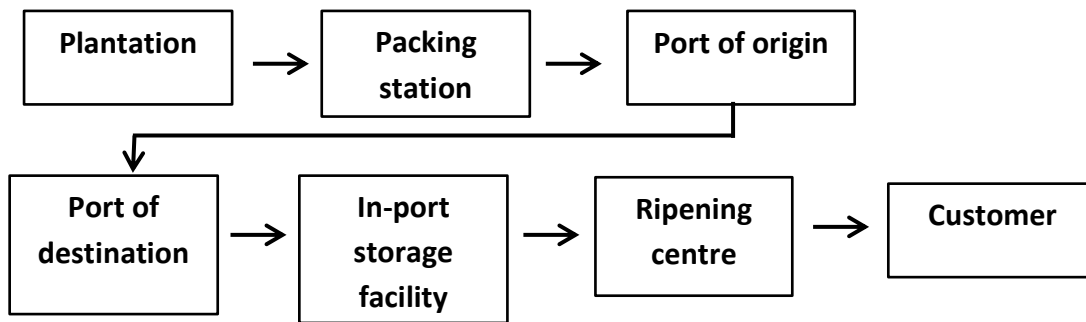
1214 **FIGURE 1.** Schematic representaion of the banana cold-chain (from Chen and Notteboom (2012)).

1215

1216 **FIGURE 2.** Theoretical pathway and controlling parameters of banana GL.

1217

1218



**FIGURE 1.**

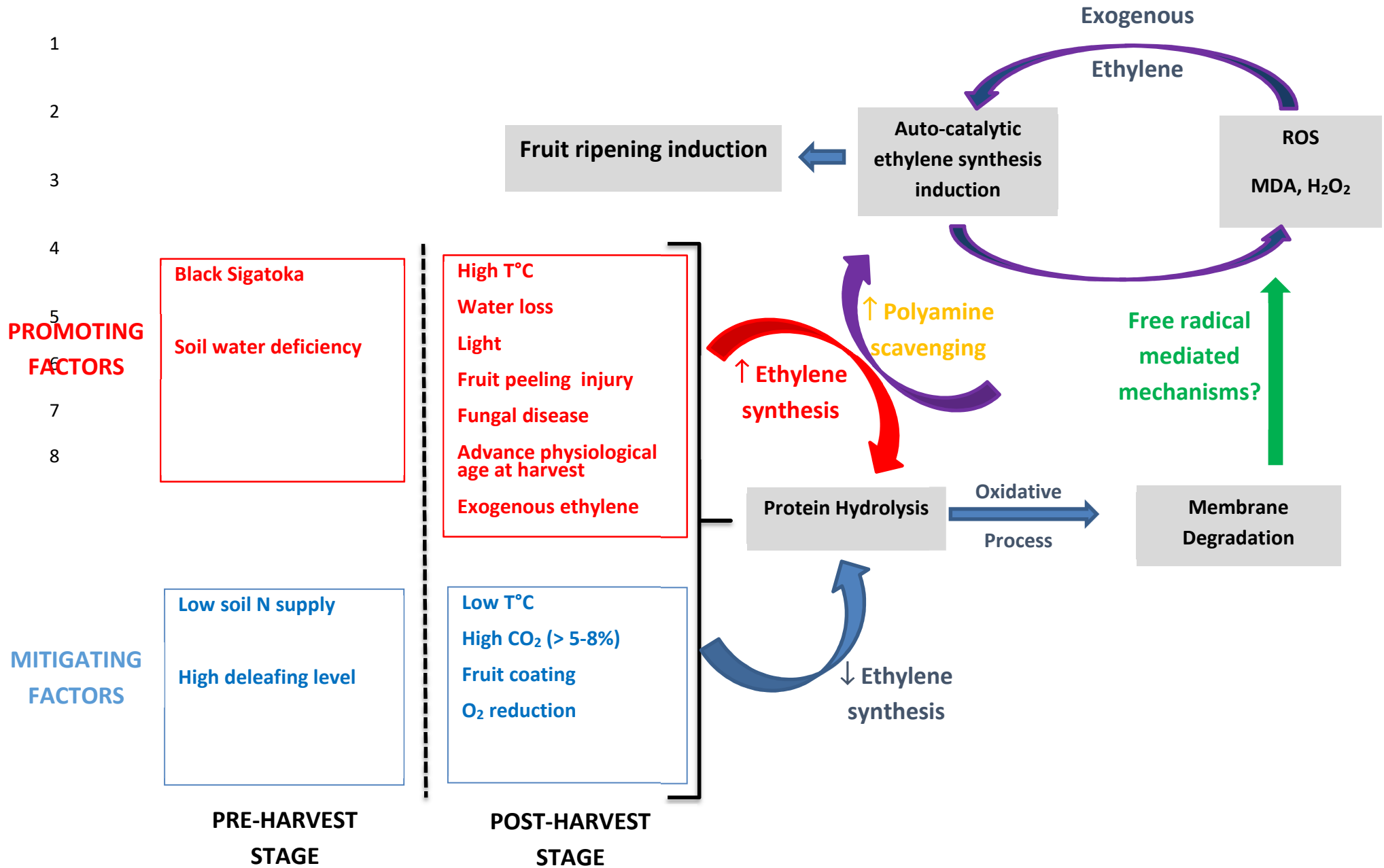


FIGURE 2