Elsevier Editorial System(tm) for Science of the Total Environment
Manuscript Draft

Manuscript Number: STOTEN-D-17-04523R1

Title: From beans to bar: a Life Cycle Assessment towards sustainable chocolate supply chain

Article Type: Research Paper

Keywords: Chocolate; Agri-food sector; Environmental sustainability; Life Cycle Assessment; Chocolate manufacturing; Environmental labeling

Corresponding Author: Dr. Francesca Recanati,

Corresponding Author's Institution: Politecnico di Milano

First Author: Francesca Recanati

Order of Authors: Francesca Recanati; Davide  Marveggio; Giovanni Dotelli

Abstract: The environmental sustainability has emerged as a crucial aspect in the agri-food sector, nevertheless environmental assessments and certifications of cocoa and chocolate are still missing. Given this gap and the increasing global demand for cocoa derivatives, this study aims to evaluate the environmental impacts of an Italian dark chocolate through a holistic cradle-to-grave Life Cycle Assessment (LCA). The impact categories assessed are acidification potential (AC), eutrophication potential (EU), global warming potential (GW), photochemical ozone creation potential (POC), ozone layer depletion potential (OD), abiotic depletion (AD) and cumulative energy demand (CED). The obtained results highlight the relevant contributions of upstream phase (63% for the ODP, 92% for EU and 99% for the AD) and core processes (39% for the GW and 49% for the CED) on the overall impacts. Specifically, cocoa provisioning and energy supply at the manufacturing plant emerged as environmental hotspots and have been deeper investigated through a sensitivity analysis. Obtained outcomes show the significant variability of the environmental impacts due to the agricultural phase (i.e., depending on agroecosystems and practices) and environmental benefits guaranteed by an efficient trigeneration system implemented in the manufacturing plant. The quantification of the environmental impacts of chocolate through LCA, the identification of the main hotspots along the supply chain and the sensitivity analysis performed in this study could effectively support chocolate companies in their pathway towards environmentally sustainable productions.

Response to Reviewers: Reviewer #1:
This manuscript carried out a holistic cradle-to-grave LCA for evaluating the environmental impacts of an Italian dark chocolate. The research is generally well done with a clear system definition, a practical method, and concrete data. Nonetheless in my view, several major changes could be applied, as recommended below:

1. My main scientific concern regarding the experimental part of this study is that although the authors provide a descent set of data of the examined technologies based on their scope to conduct "a cradle to grave" LCA study i.e from cocoa cultivation sites to final product manufacturing

and delivering in Italy, several important data concerning the system boundaries adopted in this study are not provided. These include: transportation of raw materials (fertilizers, agrochemicals, fuel consumption, irrigation etc.) to the cultivation sites as well as emission data regarding their manufacture, data collection methods, treatment of data in estimating the inventory and type of assigned burdens considered. For instance, since (L. 319-321) "the extraction of zinc, lead and copper used in the production of inorganic fertilizers, pesticides and insecticides, and the application of inorganic chemicals generate 84% of total impacts on abiotic depletion" and Peru or Ghana are not fertilizer producing countries, it is therefore evident that an in-depth analysis of the aforementioned information will enhance the credibility and accuracy of the study.

Response: We thank the reviewer for the comment and we improved the description of system boundaries analysis of the cultivation phase. For the sake of clearness, the Peruvian cocoa does not need any external inputs (i.e., fertilizer, agrochemicals or irrigation water), the data have been directly provided by the cocoa producer and the estimated impacts of UP1 (Figure 3) are due to the transportation of raw cocoa beans from the agricultural production site to the location, where sun-drying and fermentation take place. On the other hand, for other cocoa beans we used data from database, which include both the production of external inputs required by the agricultural production as well as their transportation to the plantation. The reviewed manuscript includes updated information about cocoa production thanks to the new release of ecoinvent database v3.3, in which complete inventories describing the cultivation of cocoa beans have been included. Among the available data (Ivory Coast, Indonesia and Ghana), we selected the RoW (Rest of the Word) alternative, because the main suppliers of the company under study (i.e., Uganda and Dominican Republic) are not included in the actual version of the database. The new data allowed to improve the LCIA results and to guarantee a better coherence among the different system boundaries.

2. The authors did not present energetic impacts (i.e CED or GER) on the overall cradle-to-grave LCA performance from the different scenarios, which is a crucial factor for the long-term sustainability of each allocation and alternative scenario assessed. Given the fact that the inventory results were based on both flows of materials and energy along with the necessity to evaluate the impact of several energy-intensive phases on the lice-cycle of the dark chocolate such as tempering, roasting, transportation and others, evaluation of the energy consumption should be definitely provided.

Response: We thank the reviewer for the suggestion and we included the assessment of the CED indicator.

3. There are several places where the methods are poorly described and where it cannot be derived the reason why or/and what the authors have done. The clearest example is the assumptions made. For instance, the authors state that (L. 402-405) "In order to make the three scenarios comparable, diesel consumption is not considered" since "Ntiamoah and Afrane (2008) do not specify whether the purpose of this input is the cocoa cultivation or the production of its derivatives???" and even "while for the Ecuadorian 404 cocoa it is specifically consumed in the agricultural phase". The selection of this assumption is totally

confusing given its importance in previous LCA studies and it should be therefore considered included in the LCA.

Response: We thank the reviewer for the comment and we improved and integrated the description of the assumptions adopted in the study. Referring to the specific assumption cited above, we have improved the sensitivity analysis on cocoa provisioning (section 5.2) thanks to the accurate information provided by the new release of Ecoinvent database v3.3 (as explained above).

4. L. 439-440. Authors state that ¨Results show that the trigeneration system enables to reduce impacts from 25% to 91%, on the global warming and on the abiotic depletion categories, respectively ¨. This finding is common and predictable. Therefore I believe that an in-depth analysis of the main characteristics of this system in the studied manufacturing routes will provide new insights how and where an energy saving can be achieved in the future (also in other related industries).

Response: The benefits guaranteed by the trigeneration systems are distributed among the unit processes composing the manufacturing phase (i.e., UP8, UP9, UP10, UP11) according to their energy requirement (reported in Table 2), with highest fraction attributable to production of cocoa liquor and the conching phase (27% and 32% of the energy provided by the trigeneration system, respectively). Nevertheless, the production process has just been renovated with the inclusion of best available technologies and each production stage has been optimized. Therefore, for the immediate future it is difficult to forecast possible energy savings at least until new technologies will be available.

5. Comparison between three different alternative allocation scenarios (base case, economic, mass-based) is a major output of the research. However, the environmental impact assessment alone cannot justify the feasibility and effectiveness of economic or mass-based. A cost and benefit analysis may hereby help a lot. The economic cost of both allocation scenarios is better to be made/discussed in particular.

Response: We totally agree with reviewer’s opinion. The assessment carried out is based on the price data of cocoa shell supplied by the Italian chocolate producer, which sells the cocoa shell (which becomes a co-product of the studied chocolate) to other companies. Unfortunately, we have no information about the “second life” of sold cocoa shells, but for the fact that they enter a new supply chain (e.g., production of animal feed or fertilizers). For this reason, we cannot analyze the costs and benefits for the cocoa-shells and we just focus on the scope of our study, i.e., the production of dark chocolate.

Other comments:
- Abstract and Graphical abstract. Please use uniform abbreviations in the whole manuscript. e.g AP instead of AC for "acidification potential" or vice versa. The same for EU, PO……etc.
Response: For the sake of clarity, we decided to report the whole name of every impact category in the Graphical Abstract.
- p.124. Why did the authors choose 1 kg on dark chocolate rather than 1 bar of 100g for functional unit? It seems that for a cradle-to-grave LCA study, the choice of a marketable product (I bar of chocolate) is more preferable. In addition, authors state that p.160-161 "the distribution of chocolate bars" is considered in the grave instead of 1 kg of chocolate. Please clarify this point and use additional references.

Response: We selected a functional unit equal to 1 kg of chocolate in accordance to the Product Category Rules of products similar to chocolate provided by Environdec and to the analyzed literature studies. Moreover, we supplied the information to convert bars into kg (1 kg of chocolate is equal to 10 bars). We corrected the sentences reported above.
-The authors should include additional references and, in particular, quote more accessible and up-to-date studies, even from their previous works. To this context, I suggest a comparison table with previous related studies to identify how this contribution adds some new insights which were not observed in previous studies and justify it. Another column with observation from each study would help in understanding the present study better.
Response: We thank the reviewer for the comment and suggestion. In Figure 2, we had already reported all the existing studies regarding the environmental impacts of cocoa and chocolate production (published between 1999 and 2016). We modified Figure 2 by adding a further line including the characteristics of the present study, as suggested. Moreover, we highlighted the contributions brought by the outcomes of this study in the discussion.
- Environmental impacts vs. Sustainability improvement. Sustainability includes environmental, social and economic aspects and mustn't be confused with only environmental improvement. Please elaborate this point referring to L.77, L. 453, L. 484 and others….
Response: We thank the reviewer for the comment and we modified the text when specifications about environmental dimension were needed.
-Limitation and scope of the study should be provided at the end.
Response: According to the LCA methodology, the scope of the study is stated in section 2.1. Concerning the limitations, we extended their analysis together with possible future development in the Discussion section.
- Figure 2. Please change "paper" with "study".
Done

- The methodological part (Sections 2 and 3) seems over long, taking 8 out of 20 pages of the text. A concise and concentrated description would be favorable. Some less relevant contents can be moved to the supplementary information or eliminated.
Response: We thank the reviewer for the comment and we tried to shorten this part. These two sections describe the methodology adopted in the study, but they are a fundamental part of our research, since they include the model of the system and the collected data (section 2) as well as the LCI (section 3) which is a result of our data collection and analysis. Therefore, we would prefer to maintain a precise description of the system under study, as well as all the LCA steps to allow the reader to have detailed information about our work. Both these elements were not reported in details in other existing studies and we think this is a peculiarity of our study.
- The readers may wonder what are the new contributions the present research can provide? What are the policy implications? Are proposed scenarios implemented in the plant in Italy or elsewhere? If not, why? Please offer a deeper policy relevant analysis to answer these questions.
Response: We thank the reviewer for the comment and we tried to improve this point. As previously said, we modified Figure 2 by adding a further line including the characteristics of the present study and we better highlighted the contributions brought by the outcomes of this study in the Discussion.

- Though the language does not bear on their scientific work, the authors may use an English editing service to polish English writings. Some examples to be improved are:
- L.61. Please insert "the" before "tropical"
Done

- L.95. Please change "First" with "Firstly"
Done

- L.103. Please change "does" with "do".
Done

Reviewer #2:
This study is of great interest for the chocolate industry and shows a detailed and properly carried out investigation.
It is quite long and a lot of supplementary materials is provided.
Some revisions are suggested.
- In the graphical abstract non-conventional abbreviations should be avoided. The same is for the highlights.

Response: For the sake of clarity, we decided to report the whole name of the impact category both in the Graphical Abstract and in the Highlights.
- "Cocoa derivatives are not present among the certified products" cocoa is for sure one of the most product for which sustainability concepts started to be applied, especially social-ethical responsibilities. So fairy trade certifications are common for cocoa products. There exists also Rainforest Alliance Certified Cocoa. A reference to this kind of certifications which are, anyway correlated to sustainability, should be made.

Response: We thank the reviewer for the suggestion and we added a paragraph about the abovementioned certifications in the introduction.
- Fig. 1 is not necessary.
Response: Since it underlines the importance of cocoa trade, we would prefer to keep it.
- Section 2.1 is more appropriate for the introduction, or rather you could simply state that you carried out all the stages of the LCA study.
Response: We thank the reviewer for the comment, but we prefer to report all the stages characterizing the LCA methodology (we summarized it in Section 2 incipit).
- The main ingredients are not clear. Maybe could you note reveal the exact recipe due to industrial secrets obligations? Was the recipe including cocoa powder? Not sugar? Then was a 100 % dark chocolate?
Response: We reported the table listing all the ingredients composing the chocolate under study (Table 1).
- "An aluminum foil (1.8 g) and a cardboard (11.8 g)" for functional unit? From supplementary materials, one would say for 100 g. It becomes clear in section 3 but it should be better to explain here.
Response: We thank the reviewer for the suggestion. In Table 1 we reported the information about the dark chocolate bar packaging (i.e. 1.8 g of aluminum and 11.8 g of cardboard).
- Lines 127-131, partly already said in the introduction.
Response: We thank the reviewer for the comment and we deleted the sentence and moved some information in the introduction.
- Is not the refining phase carried out? Maybe it is carried out during conching? You refer to refining at line 263. What about molding

and cooling after tempering and before packing? (not included in the figure but commented in the text).
Response: In the LCA we aggregated some phases of the chocolate manufacturing because of the aggregation detail of primary data. As the reviewer pointed out, the UP10 (conching) includes mixing, refining and conching phases as well as the UP 11 (TP) includes tempering, molding, cooling and packaging processes. The reviewer could find the correction in Figure 3 caption and in the improved description of chocolate production in the main text.

- I don't understand the reference to the PCR of sugar.

Response: An important feature of EPD declaration is that products of the same type could be compared if the LCA is performed following the relative PCR. The PCR doesn’t exist for chocolate or cocoa derivatives. We use the PCR of sugar as reference to strengthen the choice of functional unit and system boundaries. We hope that the international EPD system will soon provide a cocoa PCR.

-Line 152: tempering is not carried out during conching.

Response: As for the refining phase, we corrected the main text.

- Line 193: not clear the mass allocation criterion.

Response: The criterion is based on data about the produced mass of the three co-products by the Italian company during the reference years. For instance, the RMP unit (UP9) has four outputs: cocoa liquor, cocoa powder, cocoa butter and cocoa shells. We allocated zero impacts to cocoa shells (see section 2.1.4) and impacts to liquor, butter and powder were allocated using a mass criterion (i.e. the mass of cocoa derivatives outgoing UP9). Possible implications of this hypothesis are investigated through a sensitivity analysis presented in Section 5.1

- Is LCIA life cycle impact assessment?

Response: As explicitly stated in line 109, LCIA is the Life Cycle Impact Assessment.

- Section 3: why do not put this section under materials and methods or under "Results and discussion"? Lines 263-270: what about the cocoa liquor, cocoa butter and powder that are produced but not used for chocolate production (if this holds also for butter and powder)?

I imagine this study is the result of large investigation but when you discuss deeply the upstream, core and donwnstream processes, some things just seem to "pop from nowhere". For example lines 319-321, or 346-347.
Response: These are by- or co-products which are out the scope of this specific LCA study. As typically done in LCA, the co-products are mentioned to explain the allocation procedure adopted to split the consumption of resources among the different products, but, since the study focuses on a specific product and they are outside system boundaries their impacts are not described.

- You compared different possible cocoa provisioning scenarios. But, could not there be limitations to the choice of cocoa provisions based on cocoa beans quality?

Response: We thank the reviewer for the comment and we totally agree with him. The selection of scenarios is made only for environmental analysis (scope of our study). As mentioned in the discussion part, the environmental analysis should be integrated with some quality indicators. Moreover, the scenarios only refer to the fraction of cocoa called “other cocoa” used to produce powder and butter and not for the Peruvian cocoa used to produce cocoa liquor, which, in our case, is the cocoa which makes the quality of the product.

- The results reported in section 5.3 were expected, however it can be still interesting to know the advantages due to trigeneration.

Response: The benefits guaranteed by the trigeneration systems are distributed among the unit processes composing the manufacturing phase (i.e., UP8, UP9, UP10, UP11) according to their energy requirement (reported in Table 2), with highest fraction attributable to production of cocoa liquor and the conching phase (27% and 32% of the energy provided by the trigeneration system, respectively). Nevertheless, the production process has just been renovated with the inclusion of best available technologies and each production stage has been optimized. Therefore, for the immediate future it is difficult to forecast possible energy savings at least until new technologies will be available.

- Section 6 should be shortened moving the reference to literature to the previous sections and leaving here only basic conclusions.

Response: We thank the reviewer for the suggestion. Nevertheless, we prefer to maintain an integrated discussion including both LCA and in-depth analysis ones.

POLITECNICO
MILANO 1863

DIPARTIMENTO DI ELETTRONICA
INFORMAZIONE E BIOINGEGNERIA

Milan, September 8th 2017

Dear Editor,

Please find enclosed a revised version of manuscript STOTEN-D-17-04523, entitled "*From beans to bar: a Life Cycle Assessment towards sustainable chocolate supply chain*", by Davide Marveggio, Giovanni Dotelli and myself.

We are grateful to the two anonymous referees for their useful comments, which have greatly helped us to improve the manuscript. As you will see in the revised version of the paper, we have taken into account all their suggestions.

Here below, we enclose a point-by-point reply (roman font) to each of the comments provided by the referees (*italic font*). Hoping that our work is now suitable for the qualitative standards of your journal, we look forward to your final decision.

Best regards,

Francesca Recanati

Francesca Recanati

Reviewer #1:

This manuscript carried out a holistic cradle-to-grave LCA for evaluating the environmental impacts of an Italian dark chocolate. The research is generally well done with a clear system definition, a practical method, and concrete data. Nonetheless in my view, several major changes could be applied, as recommended below:

1. My main scientific concern regarding the experimental part of this study is that although the authors provide a descent set of data of the examined technologies based on their scope to conduct "a cradle to grave" LCA study i.e from cocoa cultivation sites to final product manufacturing and delivering in Italy, several important data concerning the system boundaries adopted in this study are not provided. These include: transportation of raw materials (fertilizers, agrochemicals, fuel consumption, irrigation etc.) to the cultivation sites as well as emission data regarding their manufacture, data collection methods, treatment of data in estimating the inventory and type of assigned burdens considered. For instance, since (L. 319-321) "the extraction of zinc, lead and copper used in the production of inorganic fertilizers, pesticides and insecticides, and the application of inorganic chemicals generate 84% of total impacts on abiotic depletion" and Peru or Ghana are not fertilizer producing countries, it is therefore evident that an in-depth analysis of the aforementioned information will enhance the credibility and accuracy of the study.

   <u>Response:</u> *We thank the reviewer for the comment and we improved the description of system boundaries analysis of the cultivation phase. For the sake of clearness, the Peruvian cocoa does not need any external inputs (i.e., fertilizer, agrochemicals or irrigation water), the data have been directly provided by the cocoa producer and the estimated impacts of UP1 (Figure 3) are due to the transportation of raw cocoa beans from the agricultural production site to the location, where sun-drying and fermentation take place. On the other hand, for other cocoa beans we used data from database, which include both the production of external inputs required by the agricultural production as well as their transportation to the plantation. The reviewed manuscript includes updated information about cocoa production thanks to the new release of ecoinvent database v3.3, in which complete inventories describing the cultivation of cocoa beans have been included. Among the available data (Ivory Coast, Indonesia and Ghana), we selected the RoW (Rest of the Word) alternative, because the main suppliers of the company under study (i.e., Uganda and Dominican Republic) are not included in the actual version of the database. The new data allowed to improve the LCIA results and to guarantee a better coherence among the different system boundaries.*

2. The authors did not present energetic impacts (i.e CED or GER) on the overall cradle-to-grave LCA performance from the different scenarios, which is a crucial factor for the long-term sustainability of each allocation and alternative scenario assessed. Given the fact that the inventory results were based on both flows of materials and energy along with the necessity to evaluate the impact of several energy-intensive phases on the lice-cycle of the dark chocolate

such as tempering, roasting, transportation and others, evaluation of the energy consumption should be definitely provided.

<u>Response:</u> *We thank the reviewer for the suggestion and we included the assessment of the CED indicator.*

3. There are several places where the methods are poorly described and where it cannot be derived the reason why or/and what the authors have done. The clearest example is the assumptions made. For instance, the authors state that (L. 402-405) "In order to make the three scenarios comparable, diesel consumption is not considered" since "Ntiamoah and Afrane (2008) do not specify whether the purpose of this input is the cocoa cultivation or the production of its derivatives???" and even "while for the Ecuadorian 404 cocoa it is specifically consumed in the agricultural phase". The selection of this assumption is totally confusing given its importance in previous LCA studies and it should be therefore considered included in the LCA.

   <u>Response:</u> *We thank the reviewer for the comment and we improved and integrated the description of the assumptions adopted in the study. Referring to the specific assumption cited above, we have improved the sensitivity analysis on cocoa provisioning (section 5.2) thanks to the accurate information provided by the new release of Ecoinvent database v3.3 (as explained above).*

4. L. 439-440. Authors state that ¨Results show that the trigeneration system enables to reduce impacts from 25% to 91%, on the global warming and on the abiotic depletion categories, respectively ¨. This finding is common and predictable. Therefore I believe that an in-depth analysis of the main characteristics of this system in the studied manufacturing routes will provide new insights how and where an energy saving can be achieved in the future (also in other related industries).

   <u>Response:</u> *The benefits guaranteed by the trigeneration systems are distributed among the unit processes composing the manufacturing phase (i.e., UP8, UP9, UP10, UP11) according to their energy requirement (reported in Table 2), with highest fraction attributable to production of cocoa liquor and the conching phase (27% and 32% of the energy provided by the trigeneration system, respectively). Nevertheless, the production process has just been renovated with the inclusion of best available technologies and each production stage has been optimized. Therefore, for the immediate future it is difficult to forecast possible energy savings at least until new technologies will be available.*

5. Comparison between three different alternative allocation scenarios (base case, economic, mass-based) is a major output of the research. However, the environmental impact assessment alone cannot justify the feasibility and effectiveness of economic or mass-based. A

cost and benefit analysis may hereby help a lot. The economic cost of both allocation scenarios is better to be made/discussed in particular.

*<u>Response:</u> We totally agree with reviewer's opinion. The assessment carried out is based on the price data of cocoa shell supplied by the Italian chocolate producer, which sells the cocoa shell (which becomes a co-product of the studied chocolate) to other companies. Unfortunately, we have no information about the "second life" of sold cocoa shells, but for the fact that they enter a new supply chain (e.g., production of animal feed or fertilizers). For this reason, we cannot analyze the costs and benefits for the cocoa-shells and we just focus on the scope of our study, i.e., the production of dark chocolate.*

Other comments:

- Abstract and Graphical abstract. Please use uniform abbreviations in the whole manuscript. e.g AP instead of AC for "acidification potential" or vice versa. The same for EU, PO……etc.

*<u>Response:</u> For the sake of clarity, we decided to report the whole name of every impact category in the Graphical Abstract.*

- p.124. Why did the authors choose 1 kg on dark chocolate rather than 1 bar of 100g for functional unit? It seems that for a cradle-to-grave LCA study, the choice of a marketable product (I bar of chocolate) is more preferable. In addition, authors state that p.160-161 "the distribution of chocolate bars" is considered in the grave instead of 1 kg of chocolate. Please clarify this point and use additional references.

*<u>Response:</u> We selected a functional unit equal to 1 kg of chocolate in accordance to the Product Category Rules of products similar to chocolate provided by Environdec and to the analyzed literature studies. Moreover, we supplied the information to convert bars into kg (1 kg of chocolate is equal to 10 bars). We corrected the sentences reported above.*

-The authors should include additional references and, in particular, quote more accessible and up-to-date studies, even from their previous works. To this context, I suggest a comparison table with previous related studies to identify how this contribution adds some new insights which were not observed in previous studies and justify it. Another column with observation from each study would help in understanding the present study better.

*<u>Response:</u> We thank the reviewer for the comment and suggestion. In Figure 2, we had already reported all the existing studies regarding the environmental impacts of cocoa and chocolate production (published between 1999 and 2016). We modified Figure 2 by adding a further line including the characteristics of the present study, as suggested. Moreover, we highlighted the contributions brought by the outcomes of this study in the discussion.*

- Environmental impacts vs. Sustainability improvement. Sustainability includes environmental, social and economic aspects and mustn't be confused with only environmental improvement. Please elaborate this point referring to L.77, L. 453, L. 484 and others….

> *Response: We thank the reviewer for the comment and we modified the text when specifications about environmental dimension were needed.*

-Limitation and scope of the study should be provided at the end.

> *Response: According to the LCA methodology, the scope of the study is stated in section 2.1. Concerning the limitations, we extended their analysis together with possible future development in the Discussion section.*

- Figure 2. Please change "paper" with "study".

> *Done*

- The methodological part (Sections 2 and 3) seems over long, taking 8 out of 20 pages of the text. A concise and concentrated description would be favorable. Some less relevant contents can be moved to the supplementary information or eliminated.

> *Response: We thank the reviewer for the comment and we tried to shorten this part. These two sections describe the methodology adopted in the study, but they are a fundamental part of our research, since they include the model of the system and the collected data (section 2) as well as the LCI (section 3) which is a result of our data collection and analysis. Therefore, we would prefer to maintain a precise description of the system under study, as well as all the LCA steps to allow the reader to have detailed information about our work. Both these elements were not reported in details in other existing studies and we think this is a peculiarity of our study.*

- The readers may wonder what are the new contributions the present research can provide? What are the policy implications? Are proposed scenarios implemented in the plant in Italy or elsewhere? If not, why? Please offer a deeper policy relevant analysis to answer these questions.

> *Response: We thank the reviewer for the comment and we tried to improve this point. As previously said, we modified Figure 2 by adding a further line including the characteristics of the present study and we better highlighted the contributions brought by the outcomes of this study in the Discussion.*

- Though the language does not bear on their scientific work, the authors may use an English editing service to polish English writings. Some examples to be improved are:
- L.61. Please insert "the" before "tropical"

> *Done*

- L.95. Please change "First" with "Firstly"

*Done*

- L.103. Please change "does" with "do".

*Done*

Reviewer #2:
This study is of great interest for the chocolate industry and shows a detailed and properly carried out investigation.
It is quite long and a lot of supplementary materials is provided.
Some revisions are suggested.
- In the graphical abstract non-conventional abbreviations should be avoided. The same is for the highlights.

> *Response: For the sake of clarity, we decided to report the whole name of the impact category both in the Graphical Abstract and in the Highlights.*

- "Cocoa derivatives are not present among the certified products" cocoa is for sure one of the most product for which sustainability concepts started to be applied, especially social-ethical responsibilities. So fairy trade certifications are common for cocoa products. There exists also Rainforest Alliance Certified Cocoa. A reference to this kind of certifications which are, anyway correlated to sustainability, should be made.

> *Response: We thank the reviewer for the suggestion and we added a paragraph about the abovementioned certifications in the introduction.*

- Fig. 1 is not necessary.

> *Response: Since it underlines the importance of cocoa trade, we would prefer to keep it.*

- Section 2.1 is more appropriate for the introduction, or rather you could simply state that you carried out all the stages of the LCA study.

> *Response: We thank the reviewer for the comment, but we prefer to report all the stages characterizing the LCA methodology (we summarized it in Section 2 incipit).*

- The main ingredients are not clear. Maybe could you note reveal the exact recipe due to industrial secrets obligations? Was the recipe including cocoa powder? Not sugar? Then was a 100 % dark chocolate?

> *Response: We reported the table listing all the ingredients composing the chocolate under study (Table 1).*

- "An aluminum foil (1.8 g) and a cardboard (11.8 g)" for functional unit? From supplementary materials, one would say for 100 g. It becomes clear in section 3 but it should be better to explain here.

> *Response: We thank the reviewer for the suggestion. In Table 1 we reported the information about the dark chocolate bar packaging (i.e. 1.8 g of aluminum and 11.8 g of cardboard).*

-Lines 127-131, partly already said in the introduction.

> *Response: We thank the reviewer for the comment and we deleted the sentence and moved some information in the introduction.*

-Is not the refining phase carried out? Maybe it is carried out during conching? You refer to refining at line 263. What about molding and cooling after tempering and before packing? (not included in the figure but commented in the text).

> _Response:_ *In the LCA we aggregated some phases of the chocolate manufacturing because of the aggregation detail of primary data. As the reviewer pointed out, the UP10 (conching) includes mixing, refining and conching phases as well as the UP 11 (TP) includes tempering, molding, cooling and packaging processes. The reviewer could find the correction in Figure 3 caption and in the improved description of chocolate production in the main text.*

- I don't understand the reference to the PCR of sugar.

> _Response:_ *An important feature of EPD declaration is that products of the same type could be compared if the LCA is performed following the relative PCR. The PCR doesn't exist for chocolate or cocoa derivatives. We use the PCR of sugar as reference to strengthen the choice of functional unit and system boundaries. We hope that the international EPD system will soon provide a cocoa PCR.*

-Line 152: tempering is not carried out during conching.

> _Response:_ *As for the refining phase, we corrected the main text.*

-Line 193: not clear the mass allocation criterion.

> _Response:_ *The criterion is based on data about the produced mass of the three co-products by the Italian company during the reference years. For instance, the RMP unit (UP9) has four outputs: cocoa liquor, cocoa powder, cocoa butter and cocoa shells. We allocated zero impacts to cocoa shells (see section 2.1.4) and impacts to liquor, butter and powder were allocated using a mass criterion (i.e. the mass of cocoa derivatives outgoing UP9). Possible implications of this hypothesis are investigated through a sensitivity analysis presented in Section 5.1*

-Is LCIA life cycle impact assessment?

> _Response:_ *As explicitly stated in line 109, LCIA is the Life Cycle Impact Assessment.*

-Section 3: why do not put this section under materials and methods or under "Results and discussion"? Lines 263-270: what about the cocoa liquor, cocoa butter and powder that are produced but not used for chocolate production (if this holds also for butter and powder)? I imagine this study is the result of large investigation but when you discuss deeply the upstream, core and donwnstream processes, some things just seem to "pop from nowhere". For example lines 319-321, or 346-347.

> _Response:_ *These are by- or co-products which are out the scope of this specific LCA study. As typically done in LCA, the co-products are mentioned to explain the allocation procedure adopted to split the consumption of resources among the different products, but, since the study focuses on a specific product and they are outside system boundaries their impacts are not described.*

- You compared different possible cocoa provisioning scenarios. But, could not there be limitations to the choice of cocoa provisions based on cocoa beans quality?

> *Response:* *We thank the reviewer for the comment and we totally agree with him. The selection of scenarios is made only for environmental analysis (scope of our study). As mentioned in the discussion part, the environmental analysis should be integrated with some quality indicators. Moreover, the scenarios only refer to the fraction of cocoa called "other cocoa" used to produce powder and butter and not for the Peruvian cocoa used to produce cocoa liquor, which, in our case, is the cocoa which makes the quality of the product.*

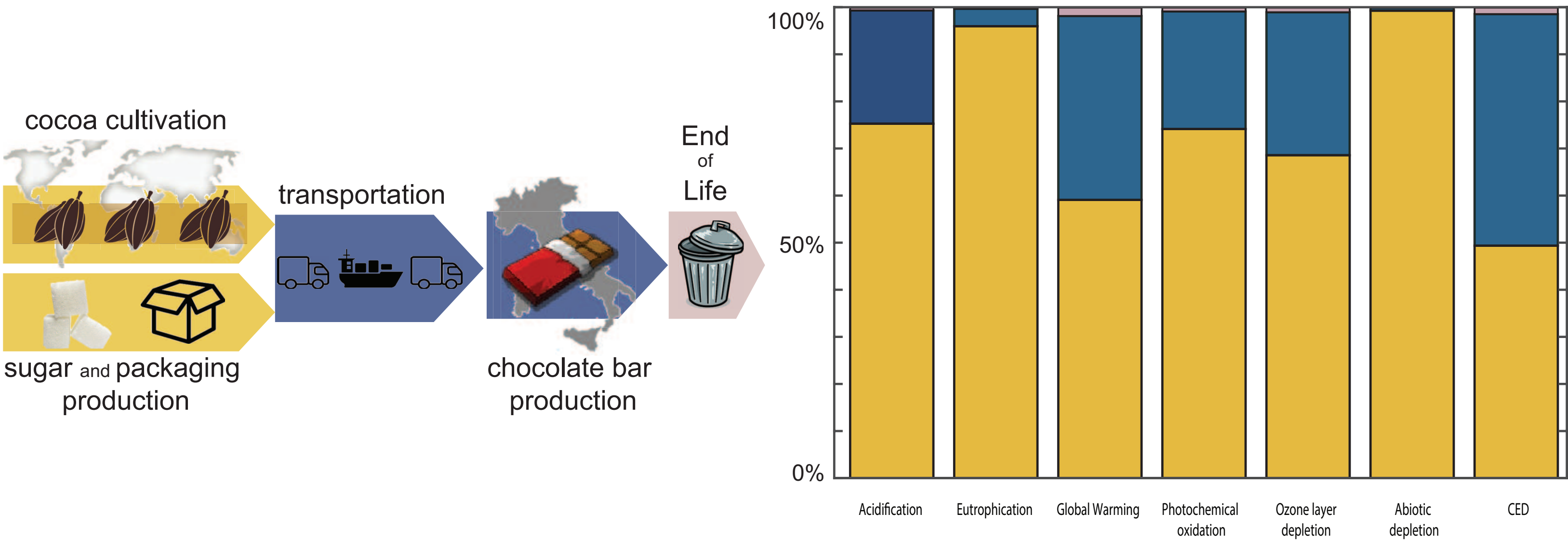
- The results reported in section 5.3 were expected, however it can be still interesting to know the advantages due to trigeneration.

> *Response:* *The benefits guaranteed by the trigeneration systems are distributed among the unit processes composing the manufacturing phase (i.e., UP8, UP9, UP10, UP11) according to their energy requirement (reported in Table 2), with highest fraction attributable to production of cocoa liquor and the conching phase (27% and 32% of the energy provided by the trigeneration system, respectively). Nevertheless, the production process has just been renovated with the inclusion of best available technologies and each production stage has been optimized. Therefore, for the immediate future it is difficult to forecast possible energy savings at least until new technologies will be available.*

- Section 6 should be shortened moving the reference to literature to the previous sections and leaving here only basic conclusions.

> *Response:* *We thank the reviewer for the suggestion. Nevertheless, we prefer to maintain an integrated discussion including both LCA and in-depth analysis ones.*

***Graphical Abstract**



***Highlights (for review)**

- *Holistic environmental assessments of chocolate are still missing in the literature*
- *LCA of an Italian chocolate from cocoa cultivation to packaging End-of-Life*
- *Cocoa provisioning and chocolate manufacturing emerged as environmental hotspots*
- *Highest impacts of chocolate manufacturing are on Global Warming and Cumulative Energy Demand*
- *Different cocoa provisioning scenarios could reduce impacts from -5% on Ozone Depletion to -69% on Eutrophication*

**Notes for reviewers:**

This is the revised version of the manuscript. New or rewritten text is highlighted in yellow.

Table 1 has been moved from the Supplementary Materials to main text.

Figure 8 is fully new due to the inclusion of CED indicator.

7 new references have been included.

1 reference have been deleted (Coffee PEF Technical Secratariat, 2015. PEF screening report coffee 1–127)

# From beans to bar: a Life Cycle Assessment towards sustainable chocolate supply chain

Francesca Recanati[a]*, Davide Marveggio[b], Giovanni Dotelli[c]

[a] Dipartimento di Elettronica, Informazione e Bioingegneria, Politecnico di Milano, via Ponzio 34/5, 20133, Milano, Italy

[b] Dipartimento di Scienze Agrarie e Ambientali - Produzione, Territorio, Agroenergia, Università degli studi di Milano, via Celoria 2, 20133, Milano, Italy

[c] Dipartimento di Chimica, Materiali e Ingegneria Chimica "G. Natta", Politecnico di Milano, Piazza Leonardo da Vinci 32, 20133 Milano, Italy

* Corresponding author. Tel.: +390223994030; fax: +390223993412

*E-mail address:* francesca.recanati@polimi.it (F. Recanati).

## Abstract

The environmental sustainability has emerged as a crucial aspect in the agri-food sector, nevertheless environmental assessments and certifications of cocoa and chocolate are still missing. Given this gap and the increasing global demand for cocoa derivatives, this study aims to evaluate the environmental impacts of an Italian dark chocolate through a holistic *cradle-to-grave* Life Cycle Assessment (LCA). The impact categories assessed are acidification potential (AC), eutrophication potential (EU), global warming potential (GW), photochemical ozone creation potential (POC), ozone layer depletion potential (OD), abiotic depletion (AD) and cumulative energy demand (CED). The obtained results highlight the relevant contributions of upstream phase (63% for the ODP, 92% for EU and 99% for the AD) and core processes (39% for the GW and 49% for the CED) on the overall impacts. Specifically, cocoa provisioning and energy supply at the manufacturing plant emerged as environmental hotspots and have been deeper investigated through a sensitivity analysis. Obtained outcomes show the significant variability of the environmental impacts due to the agricultural phase (i.e., depending on agroecosystems and practices) and environmental benefits guaranteed by an efficient trigeneration system implemented in the manufacturing plant. The quantification of the environmental impacts of chocolate through LCA, the identification of the main hotspots along the supply chain and the sensitivity analysis performed in this study could effectively support chocolate companies in their pathway towards environmentally sustainable productions.

## Keywords

Chocolate, Agri-food sector, Environmental sustainability, Life Cycle Assessment, Chocolate manufacturing, Environmental labeling

## 1. Introduction

The environmental sustainability has been emerging as a pivotal aspect in the agri-food sector. Food production is responsible for more than 25% of global greenhouse gas emissions (Tilman and Clark, 2014; Solazzo et al., 2016), it bears a large share of responsibility for water consumption and contamination (Moss, 2008; Smith et al., 2014; FAO, 2016) and it uses about a half of ice-free land area on Earth as cropland and pasture (FAO, 2011; Kastner et al., 2012), which are often created through deforestation (Barona et al., 2010; Recanati et al., 2015). The chocolate supply chain is characterized by global geographical boundaries. The agricultural production of cocoa is located in tropical areas (Jacobi et al., 2014; Utomo et al., 2015) of Africa, Asia and Americas (FAO, 2017), often contributing, at least in the past, to deforestation. Once cocoa beans are harvested, fermented and dried, they are exported to major chocolate producer countries located in the temperate band like Europe and Northern America (Perez Neira, 2016). At the manufacturing plant, a complex industrial transformation takes place in order to obtain derivative products like chocolate, cocoa powder and butter. The global demand for cocoa derivatives and chocolate has tripled since the sixties and an increment of about +91% has been registered in the last 20 years (Figure 1) (FAO, 2017). Specifically, from 90's Asian and African countries showed an increase of cocoa supply of +337% and +894%, respectively (FAO, 2017). Despite this recent increment, the per-capita consumption in Asian and African countries remains far below the global average and this further emphasizes the growth in demand of cocoa derivatives forecasted for the forthcoming years (www.statista.com).

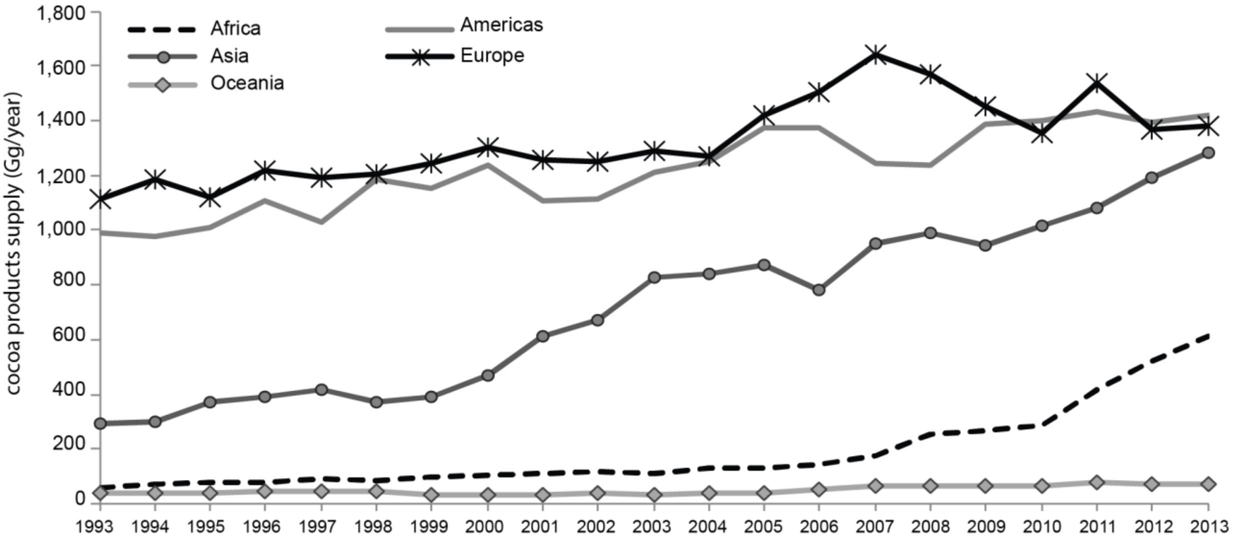
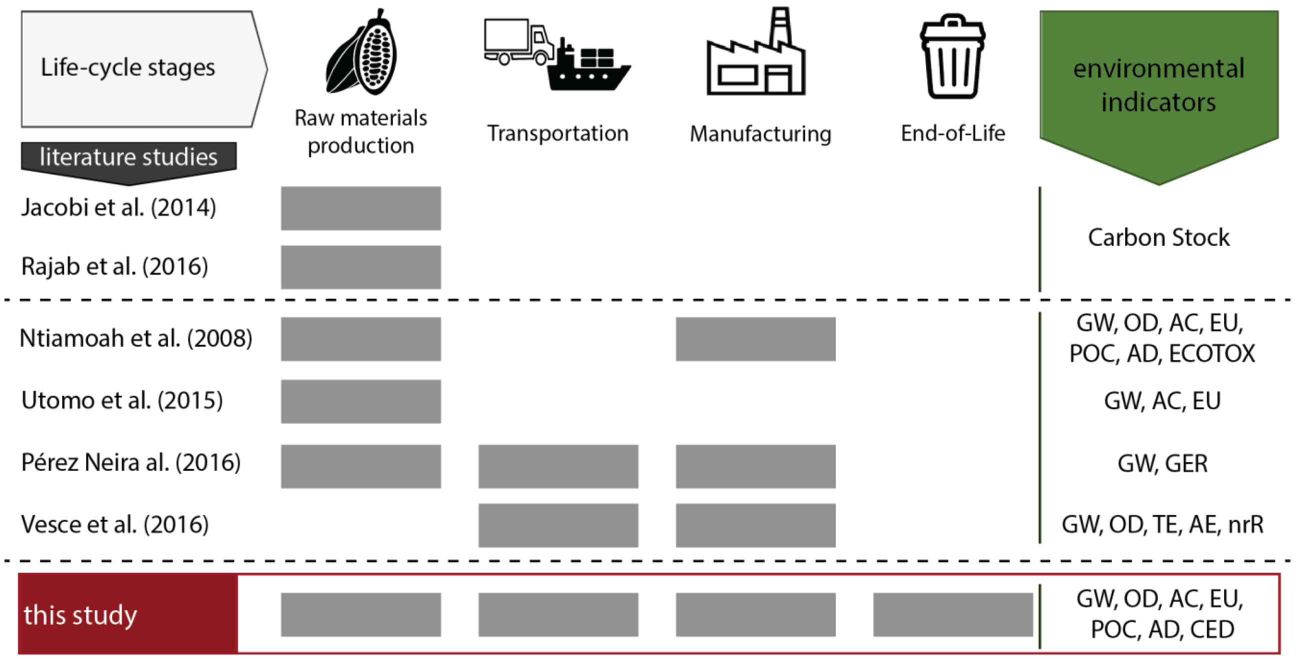


**Figure 1. Cocoa products supply statistics for the five continents (1993-2013) (FAO, 2017)**

Given the growing attention to food-related environmental impacts, food companies showed a large and active participation in environmental research and labeling (International EPD System, 2016; Bonamente et al., 2016; Buratti et al., 2017). In the last decade, the cocoa sector showed an increase in organic and fair trade certifications highlighting efforts in the environmental and social spheres (Silva et al., 2017). Nevertheless, neither environmental certifications based on quantitative assessment like the Environmental Product Declaration by the International EPD® System (International EPD System, 2016) nor the related Product Category Rules (PCRs) (ISO, 2006c) currently exist for this sector. In the literature, the environmental dimension of cocoa and chocolate supply chain has been partially investigated (Bessou et al., 2013) and, to the authors' knowledge, no studies have performed a cradle-to-grave and multiple environmental indicators Life Cycle Assessment. For instance, existing studies (Figure 2) analyzed the whole life cycle of chocolate focusing on specific environmental impacts, such as global warming and energy demand (Perez Neira, 2016), while others focused on specific life-cycle steps, like the cocoa beans production (Jacobi et al., 2014; Utomo et al., 2015; Rajab et al., 2016; Ntiamoah and Afrane, 2008) or the chocolate manufacturing (Vesce et al., 2016).



| Life-cycle stages<br>literature studies | Raw materials production | Transportation | Manufacturing | End-of-Life | environmental indicators |
|---|---|---|---|---|---|
| Jacobi et al. (2014) | ▨ | | | | Carbon Stock |
| Rajab et al. (2016) | ▨ | | | | |
| Ntiamoah et al. (2008) | ▨ | | ▨ | | GW, OD, AC, EU, POC, AD, ECOTOX |
| Utomo et al. (2015) | ▨ | | | | GW, AC, EU |
| Pérez Neira al. (2016) | ▨ | ▨ | ▨ | | GW, GER |
| Vesce et al. (2016) | | ▨ | ▨ | | GW, OD, TE, AE, nrR |
| this study | ▨ | ▨ | ▨ | ▨ | GW, OD, AC, EU, POC, AD, CED |

**Figure 2. State of the art about the environmental assessment of cocoa and chocolate production. For each analyzed study we highlighted the life-cycle stages involved and the environmental indicators. Grey rectangles indicate that the life-cycle stage (column heading) is considered in the study (row heading). On the right side of the figure we reported the assessed environmental indicators (GW: Global Warming, GER: Gross Energy Requirement, OD: ozone depletion layer, TE: Terrestrial Eco-toxicity, AE: Aquatic Eco-toxicity, nrR: non-renewable primary resources, AC: Acidification, EU: Eutrophication, POC: Photo-Chemical Oxidation, AD: Abiotic Depletion, ECOTOX: Freshwater-, Human- and Terrestrial eco-toxicity; CED: Cumulative Energy Demand). In the last row, we reported the information related to the present study.**

Given the continuous increase in cocoa derivatives demand and the existing literature gap, further studies are fundamental to support chocolate producers in assessing, and eventually improving, the environmental sustainability of their production. This study gives a contribution to this issue by assessing the environmental performances of a dark chocolate with the aim of highlighting the main environmental hotspots along the entire supply chain. This is accomplished through two main steps. Firstly, a *cradle-to-grave* LCA is performed according to the ISO 14040–14044 (ISO, 2006a, 2006b). A detailed inventory was created in collaboration with an Italian company characterized by a recently renovated production plant. The data survey covered the whole supply chain, with a detailed focus on the manufacturing stage. In the second part of the study, a sensitivity analysis is performed to evaluate the influence of alternative scenarios of the life cycle phases, which emerged as environmental hotspots from the LCA results.

## 2. Materials and Methods

The environmental impacts of dark chocolate are assessed through the LCA, a methodology that observes and analyses a product over its entire life cycle (ISO, 2006a, 2006b). In the following sections, all the LCA stages (i.e., goal and scope definition, Life Cycle Inventory or LCI, Life Cycle Impact Assessment or LCIA, and interpretation of results) are performed.

## 2.1. Goal and scope definition

The goal of this LCA is to assess the environmental impacts of an Italian dark chocolate adopting a *cradle-to-grave* approach.

### 2.1.1. Dark chocolate characterization

The main ingredients composing the dark chocolate under study are cocoa liquor from Peruvian cocoa beans (50.1%), and butter and powder, both from cocoa beans with unspecified origins (referred to as *other* cocoa beans from now on) (Table 1). Every bar is wrapped into an aluminum foil (1.8 g) and a cardboard (11.8 g). Finally, the production site is located in northern Italy.

**Table 1. Recipe and packaging of the Italian dark chocolate bar (100 g)**

| **Ingredients** | **Percentage** |
|---|---|
| Cocoa Liquor | 50.1% |
| Cocoa Butter | 20.2% |
| Sugar | 13.7% |
| Cocoa Powder | 16.0% |
| Vanilla Extract | <0.1% |
| **Packaging** | **Mass** |
| Aluminum Foil | 1.8 g |
| Cardboard | 11.8 g |

### 2.1.2. Functional Unit and System Boundaries

The Functional Unit (FU) analyzed is 1 kg of dark chocolate (corresponding to 10 bars of 100 g) and the relative packaging. Figure 3 shows the system boundaries and the unit processes composing the production system, grouped into upstream, core and downstream processes (International EPD

System, 2015a). Since no PCRs exist for cocoa and its derivatives, the methodological approach followed in this study has been developed according to existing PCRs of other food commodities. Specifically, the system boundaries and the division into upstream, core and downstream followed the PCR of sugar (”*Refined sugar from sugar beet”,* UN CPC 234).

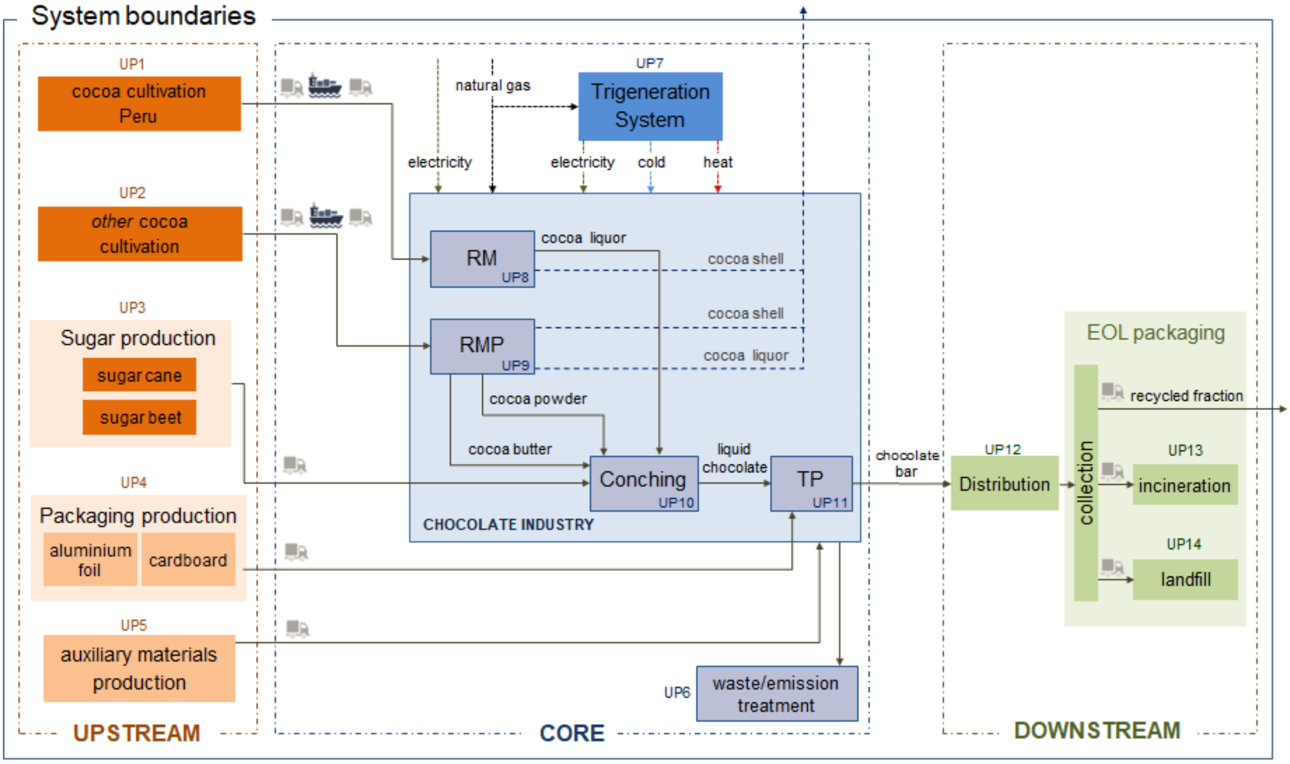


**Figure 3. Production process scheme and system boundaries of the LCA of 1 kg of dark chocolate (RM: *Roasting and milling;* RMP: *roasting, milling and pressing;* Conching: *mixing, refining and conching;* TP: *tempering, molding, cooling and packing*; EOL; *end-of-life).***

The main unit processes are here briefly described following the upstream, core and downstream partitioning (see Table 2 for a summary). Upstream processes comprehend the production of raw cocoa, other ingredients (e.g., sugar cane and sugar beet), packaging (i.e., cardboards and aluminum foils) and auxiliary materials required by the production process (e.g., lubricant oil, detergent, jute). Core processes include the transportation of all the aforementioned inputs from the respective production sites to the chocolate factory in northern Italy, the manufacturing of dark chocolate and the treatment of industrial waste. Within the manufacturing site, cocoa beans are winnowed, pre-roasted to separate cocoa shells and, then, chipped. Consequently, two alternative processes can be performed to convert cocoa beans into derivatives: the *roasting and milling* unit (*RM*, UP8) transforms Peruvian cocoa beans into cocoa liquor, whereas the *roasting, milling and pressing* unit (*RMP*, UP9) transforms *other* cocoa beans into either cocoa liquor, cocoa powder or butter. The UP10 includes the mixing of chocolate ingredients (Peruvian cocoa liquor, cocoa butter, sugar, and cocoa paste), the subsequent refining, and the conching process. The obtained liquid chocolate is tempered (*TP*), i.e., is thermally treated to become hard, durable and melty at body temperature. One kilogram of tempered chocolate is poured into molds and, once cooled, it is wrapped into an aluminum foil and in a cardboard (UP11). The majority of energy required by the chocolate manufacturing is supplied by a methane-powered trigeneration system (UP7) installed in the factory. Electricity, thermal and cold energy correspond to 50%, 35.4% and 14.6% of its total energy out-flow, respectively. Avoided impacts are not accounted for energy produced by the trigeneration plant (i.e., electricity, heat and cold). Besides the trigeneration system, the national grid satisfies further energy requirements (both electricity and natural gas). Finally, downstream processes include the distribution of chocolate, the collection of packaging waste and its End-of-Life (EoL) treatments. Transportation from the distribution center (e.g., supermarkets) to costumer's household is not considered. Moreover, we assume that during the use phase, the analyzed dark chocolate does not need refrigeration, and, given its quality, it is consumed as it is (no melting or re-tempering).

Concerning system boundaries, two methodological hypotheses drawn from the General Program of the International EPD system are adopted (International EPD System, 2015a). Firstly, a "zero-burden" hypothesis is assumed for the in-flow materials produced through a recycling process (cardboard). This implies that the impacts related to the first life of those materials do not affect the secondary one. Secondly, no benefits are attributed to the system for the energy recovery obtained through the incineration of a fraction of the outflowing waste.

### 2.1.3. Data source and quality

In the present study, both primary and secondary data are used. Primary data were provided by the Italian chocolate company and collected during the period 2014-2015. They include information regarding the Peruvian cocoa beans provisioning (from mature plantations aged between 15 and 20 years) and the manufacturing within the company. Secondary data are used, instead, for *other* cocoa beans imported from different countries in Central and South America and Africa (i.e., Dominican Republic and Uganda), sugar, packaging, auxiliary materials, and End-of-life treatments (Wernet et al., 2016). Finally, transportation distances are primarily known except for (i) sugar cane and auxiliary materials (Ecoinvent 3.3 database), (ii) *other* cocoa beans (EcotransIT, http://www.ecotransit.org) and (iii) the inputs required for their cultivation (Ecoinvent 3.3 database). Main data and sources are summarized in Table 2.

**Table 2. Inventory data types and sources**

| **Life Cycle Phase** | Technological flow | Source | Unit Process | Data Type |
|---|---|---|---|---|
| **Cultivation** | Peruvian cocoa beans | Chocolate producers | UP1 | Primary |
| | *Other* cocoa beans | Ecoinvent 3.3 | UP2 | Secondary |
| **Raw materials production** | Sugar | Ecoinvent 3.3 | UP3 | Secondary |
| | Packaging | Ecoinvent 3.3 | UP4 | Secondary |
| | Auxiliary materials | Ecoinvent 3.3 | UP5 | Secondary |
| **Transportation to manufacturing** | Peruvian cocoa beans | Chocolate producers | UP1 – company | Primary |
| | *Other* cocoa beans | http://www.ecotransit.org/ | UP2 – company | Primary |
| | Sugar from sugar beet | Chocolate producers | UP3 - company | Primary |
| | Sugar from sugar cane | Ecoinvent 3.3 | UP3 – company | Secondary |
| | Packaging | Chocolate producers | UP4 – company | Primary |
| | Auxiliary materials | Ecoinvent 3.3 | UP5 – company | Secondary |
| **Chocolate Industry** | Chocolate production | Chocolate producers | UP8/UP9/UP10/UP11 | Primary |
| | Energy Production | Chocolate producers | UP7 | Primary |
| | Industrial Waste Treatment | Ecoinvent 3.3 | UP6 | Secondary |

| | | | | |
|---|---|---|---|---|
| **Downstream phase** | Transportation | Assumed (see Section 3.3) | UP12/UP13/UP14 | Secondary |
| | EoL treatment (packaging waste) | Ecoinvent 3.3 | UP13/UP14 | Secondary |

### 2.1.4. Allocation procedure

Allocation procedures are applied in two phases. The first one regards cocoa shells, which constitutes one of the outflows of both *RM* and *RMP* (Figure 3). Although shell mass is about 13-15% of cocoa beans, they are considered as surplus because their economic value is negligible if compared to the one of cocoa derivatives. With this assumption, 100% of impacts of *RM* unit are allocated to Peruvian cocoa liquor entering the conching phase and all the impacts of the *RMP* unit are allocated to the three cocoa derivatives (liquor, powder and butter) adopting a mass allocation criterion (see Table S.6 in the Supplementary materials). The second allocation procedure regards the disaggregation of heat, cooling energy, water, auxiliary materials, wastewater and industrial waste among the unit processes in the manufacturing plant, because only aggregated data for the whole production are available. Environmental impacts are allocated to each production unit (from UP8 to UP11) adopting an energetic criterion, based on primary data of electric energy consumptions specific for each unit (Table 2). The only exception is the detergent, which is totally allocated to the *TP* unit since it is used just to wash the molds.

## 2.2. Impact Assessment Method

The flows of materials and energy collected in the LCI are translated into environmental impacts through the use of the CML-IA 2001 assessment method (baseline for eutrophication, ozone layer depletion, photochemical oxidation, global warming and abiotic depletion categories; and non-baseline for acidification category) (Guinée, 2002). This choice has been made according to the General Programme Instructions of the international EPD System (International EPD System, 2015). In addition, the Cumulative Energy Demand (CED, version 1.09) is assessed (Frischknecht et al., 2007) to calculate the direct and indirect energy uses due to the chocolate under study

(Huijbregts et al., 2006). In our study, the calculation of CED includes non-renewable (from fossil fuels, nuclear) and renewable (from wind, solar, geothermal, and water) energy sources. In agreement with the scope of our study aimed at quantifying the energy used in the chocolate supply chain, the energy embedded in the biomass of trees (such as the energy derived from the sun and captured in the biomass through photosynthesis) is excluded from the energy balance. The calculation is performed with the software PRéConsultants SimaPro 8.3. Since a VOCs[1] characterization factor for photochemical oxidation is not provided by the method, the assumption is 0.337 kg $C_2H_4$/kg VOC following the Environdec guidelines (Heijuns, 1992).

### 2.3. Sensitivity analysis

After the LCIA, a sensitivity analysis is performed to support the interpretation of the LCA results. Firstly, the methodological assumption concerning the allocation of impacts to the cocoa shells is evaluated comparing different allocation scenarios. Secondly, we assessed and compared alternative scenarios of the life cycle phase emerged as environmental hotspots from the LCIA.

## 3. Life Cycle Inventory

The inflows and outflows of energy and materials involved in the studied system are presented in the next sections following the upstream-, core- and downstream partitioning.

### 3.1. Upstream Phase

Upstream processes include the production of all the material required to produce the dark chocolate bars. As previously described, the main ingredient is cocoa from high-quality Peruvian cocoa beans (UP1). 590 g of Peruvian cocoa beans per FU are produced in mature plantations with no use of chemicals, because soil fertility is guaranteed by the litter produced by cocoa and shading trees and by the cocoa pods, which are left on the ground (Jacobi et al., 2014). Once cocoa pods are manually harvested, beans are extracted and transported to a site where the fermentation and the

---

[1] VOCs (Volatile Organic Compounds) are linked to odor compound mostly emitted in the roasting phase.

sun-drying phases occur without any energetic inputs. The production of a blend of *other* cocoa beans (UP2, 530 g per FU) used for cocoa butter and powder is modelled through Ecoinvent 3.3[2]. Sugar is the second main ingredient (137 g/FU) and its production is modelled through Ecoinvent 3.3 database (Wernet et al., 2016). The sugar provisioning is based on the fluctuations of financial market, and, according to the company statistics, a 50:50 ratio between sugar beet and sugar cane is assumed. In addition to food flows, the upstream phase includes the production of packaging (UP4) and auxiliary materials (UP5). Specifically, the 18 g/FU aluminum foil is produced in Italy from primary aluminum and it is modelled using Ecoinvent 3.3 database (i.e., starting from ingots, 0.2 mm thick sheets are obtained). Concerning the cardboard (118 g/FU), the database process “folding boxboard/chipboard {GLO}” is considered because no primary information about the production is available (Wernet et al., 2016). Finally, three auxiliary materials are included in the study and modelled through the Ecoinvent 3.3: jute bags for cocoa beans (14.5 g/FU), soap used for washing chocolate molds (375 mg/FU) and lubricant oil for the equipment service (88 mg/FU).

## 3.2. Core Phase

The core phase is composed of two main steps: the transportation of input materials from their production sites to the chocolate factory and the chocolate manufacturing.

### 3.2.1 Transportation of inputs materials

Each input material required for the chocolate production is characterized by specific itineraries and transportation means. The itinerary of cocoa beans is composed of three segments: a first route from the cultivation site to a departure port, a trans-oceanic ship transport to an Italian port and the final transportation to the chocolate production plant (Table S.1 in the Supplementary materials). According to the company statistics, we assumed that 50% *other* cocoa beans (530 g for FU) is

---

[2] Since the company major cocoa beans suppliers (i.e. Dominican Republic and Uganda) are not present in Ecoinvent 3.3, we selected “Cocoa bean {RoW}| cocoa beans production, sun dried, Alloc Rec, U”. Given the mature age of the analyzed plantations (more than 25 years), field preparation, land-use change and carbon storage are not included in the present LCI.

imported from Dominican Republic, while the other 50% from Uganda. Additional primary data regard the distances travelled by sugar from sugar beet (800 km) and packaging components (aluminum travels for 30 km and the cardboard for 230 km), while transportation mean assumed is “freight, lorry 7.5-16 metric ton, EURO4” from Ecoinvent 3.3 (Wernet et al., 2016). Finally, information on the transportation of sugar from sugar cane and auxiliary materials is taken from Ecoinvent 3.3 database.

### 3.2.2 Chocolate manufacturing

Chocolate manufacturing is composed of four unit processes from UP8 to UP11 (Figure 3) and involves all the steps necessary to transform raw cocoa beans into chocolate. UP8 produces 501 g of Peruvian cocoa liquor entering the following phase together with 160 g of cocoa powder and 202 g of cocoa butter produced in UP9. The latter produces additional 98 g of cocoa liquor, which is not used for the product under study. In the conching unit, the output of *RM* and *RMP* are mixed with 137 g of sugar. The obtained paste is refined to reduce grain size below 20 microns and then is conched to remove compounds that can alter chocolate aroma. The output is 1 kg of a liquid paste ready to be tempered and packed. Focusing on energy flows, the trigeneration plant (UP7) supplies about 98% of total electricity needed in the process (0.91 kWh out of the 0.93 kWh required by the entire process per FU), as well as heat and cold energy flows (0.64 and 0.27 kWh/FU, respectively). Additional 0.057 $Sm^3$/FU of natural gas are needed, especially due to the roasting phase. The main inputs and outputs referred to the production of one FU are summarized in Table 3.

**Table 3. Main LCI data concerning dark chocolate manufacturing (referred to FU)**

| **INPUT** | | **unit** | **Unit Process** | | | | |
|---|---|---|---|---|---|---|---|
| | | | UP8 | UP9 | UP10 | UP11 | Total |
| Energy | electricity (trigeneration) | kWh | 0.25 | 0.18 | 0.29 | 0.19 | 0.91 |
| | heat (trigeneration) | kWh | 0.18 | 0.13 | 0.21 | 0.13 | 0.64 |
| | cooling (trigeneration) | kWh | 0.07 | 0.05 | 0.08 | 0.06 | 0.27 |
| | electricity (national grid) | kWh | 0.005 | 0.004 | 0.006 | 0.004 | 0.019 |
| | natural gas (national grid) | $Sm^3$ | 0.028 | 0.018 | 0.007 | 0.004 | 0.057 |
| Ingredients | Peruvian cocoa beans | g | 590 | - | - | - | 590 |
| | *other* cocoa beans | g | - | 530 | - | - | 530 |
| | Sugar | g | - | - | 137 | - | **137** |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| Others | aluminum foil | g | - | - | - | 18 | 18 |
| | Cardboard | g | - | - | - | 118 | 118 |
| | Detergent | mg | - | - | - | 374.7 | 374.7 |
| | lubricant oil | mg | 24.2 | 17.6 | 27.8 | 18.4 | 88 |
| | water (well and grid) | l | 0.7 | 0.9 | 1.0 | 0.7 | 3.3 |
| **OUTPUT** | | | UP8 | UP9 | UP10 | UP11 | Total |
| Cocoa derivatives | Peruvian cocoa liquor | g | 501 | - | - | - | **501** |
| | cocoa powder | g | - | 160 | - | - | **160** |
| | cocoa butter | g | - | 202 | - | - | **202** |
| | cocoa shells | g | 76 | 55 | - | - | 131 |
| | *other* cocoa liquor | g | - | 98 | - | - | 98 |
| | liquid dark chocolate | g | - | - | 1,000 | - | 1,000 |
| | **Tempered and packed dark chocolate** | g | - | - | - | 1,000 | **1,000** |

Chocolate manufacturing causes direct emissions into air and water, and produces solid waste. Specific data for each unit process can be derived from air emissions samples provided by the company (Table 4). RM, RMP and conching units emit particulates, while VOCs are attributed only to *RM* and *RMP* units. The trigeneration system releases carbon monoxide and $NO_x$, while carbon dioxide is emitted by all the manufacturing units and the trigeneration system (from UP7 to UP11). The company produces different types of industrial wastes (UP6). Packaging wastes (e.g., paper, plastic, wood, metals and iron) are sent to a recycling center and only transportation to a collection site is considered. For other waste, like sludge, food waste, waste mineral oil and used fluorescent lamps, transportation is modelled through primary data (transportation distances to incineration and landfill), while the final treatment is modelled through database.

**Table 4. Main emissions data, due to the FU manufacturing, used in the LCI (TSP is Total Suspended Solids)**

| **Emissions of chocolate manufacturing** | | | **Units** | UP8 | UP9 | UP10 | UP11 | **Total** |
|---|---|---|---|---|---|---|---|---|
| **from UP8 to UP11** | Emissions to air | $CO_2$ | g | 51.9 | 37.5 | 11.8 | 7.8 | **109.0** |
| | | VOCs | mg | 80.5 | 48.4 | - | - | **128.9** |
| | | $PM_{10}$ and $PM_{2.5}$ | mg | 13.6 | 8.1 | 0.9 | - | **22.6** |
| | | | **Units** | | | | | **Total** |
| | Emissions to water | TSP | g | | | | | **1.11** |
| | | BOD5 | g | | | | | **1.35** |
| | | COD | g | | | | | **3.25** |
| | | Oils | mg | | | | | **31.68** |
| | | $SO_4$ | mg | | | | | **53.97** |

| | | | | |
|---|---|---|---|---|
| | | Cl | mg | **32.85** |
| | | $F^-$ | mg | **9.15** |
| | | P tot | mg | **2.82** |
| | | $NH_4$ | mg | **30.27** |
| | | Surfactant | mg | **115.43** |
| | | N tot (TKN) | mg | **84.48** |
| | Waste | raw sewage sludge | g | **1.69** |
| | | municipal solid waste | g | **5.19** |
| | | plastic packaging | mg | **2.26** |
| | | metals packaging | mg | **0.11** |
| | | wood packaging | mg | **1.67** |
| | | cardboard packaging | mg | **3.30** |
| | | iron and steel | mg | **0.54** |
| | | waste mineral oil | mg | **0.09** |

| | | | **Units** | **Total** |
|---|---|---|---|---|
| **UP7** | Emissions to air | $CO_2$ | g | **435.0** |
| | | $NO_x$ | g | **1.0** |
| | | CO | g | **0.7** |

### 3.3. Downstream Phase

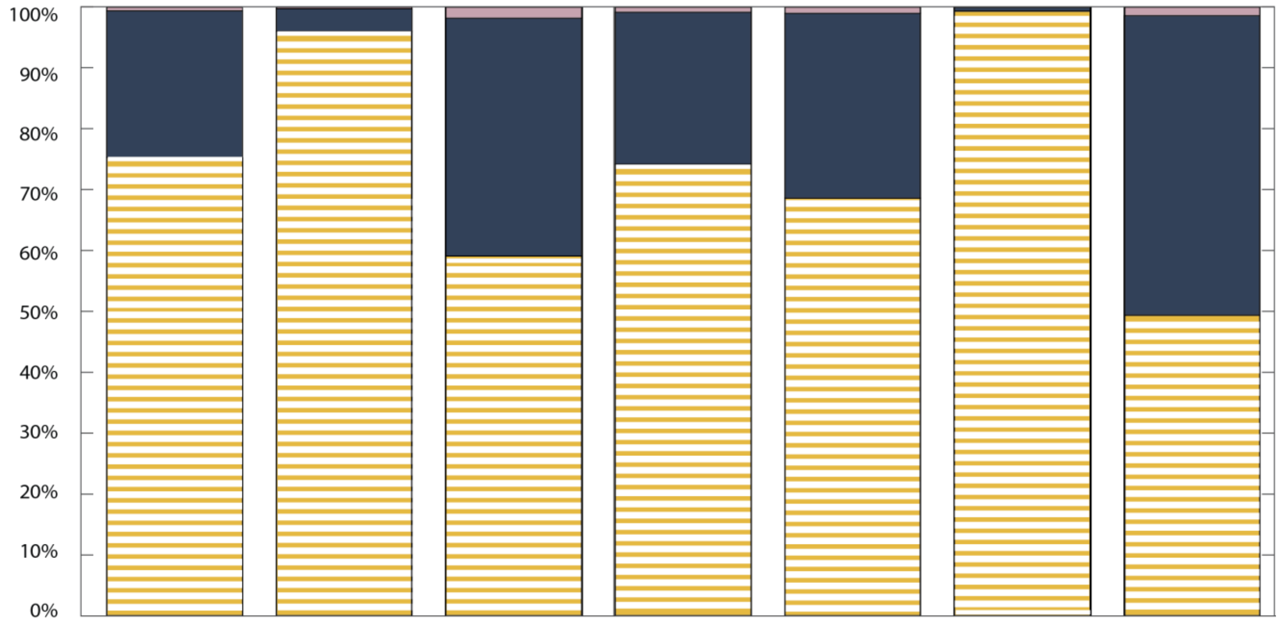
Once exited the production plant, the packed chocolate is distributed. A regional distribution within an average distance of 150 km and with a “EURO4, lorry 7.5-16 metric ton” is assumed. This is in line with the real market covered by the analyzed product. For both packaging components, EoL treatments are modelled according to the average Italian scenario (Table S.2, Supplementary materials) (CiAl, 2014; Comieco, 2015). For the recycled fraction, only transportation is considered, while for the fraction sent to disposal and incineration, both transportation and final treatment are taken into account (International EPD System, 2015b, 2014). We assumed a distance of 50 km (freight, lorry, 7,5-16 metric ton EURO4) for the collection of packaging waste (recycling, incineration and landfill) and other 50 km for transportation from the collection center to final treatment (incineration and landfill).

## 4. Life Cycle Impact Assessment

LCIA results are reported and analyzed starting from the overall process and, consequently, increasing the detail on the main unit processes.

### 4.1. Overall process

Figure 4 shows the impacts caused by the overall process disaggregated into upstream, core and downstream phases. Upstream processes have the highest contribution on abiotic depletion (1.1E-05 kg $Sb_{eq.}$, 99% of total impact), eutrophication (2.45E-02 kg $PO_4^{3-}{}_{eq.}$, 96% of total impact), acidification (1.7E-02 kg $SO_{2\ eq.}$, 75% of total impact) and photochemical oxidation categories (8.04E-04 kg $C_2H_{4eq.}$, 74% of total impact), mainly due to the cultivation of both *other* cocoa beans and sugar cane, and to packaging production. The core phase causes significant impacts on global warming (1.03E+00 kg $CO_{2eq.}$, 39% of total impact) and ozone layer depletion (1.73E-07 kg CFC-$11_{eq.}$, 30% of total impact). Both contributions are mainly due to the supply and use of natural gas in the chocolate manufacturing. The total value of CED is 33.75 MJ/FU (4% renewable and 96% non-renewable) and it is equally split between upstream and core processes (49% each). Finally, downstream processes always represent negligible contributions, which range from 0.2% on eutrophication to 1.8% on global warming category.



| | Acidification<br>kg $SO_2$ eq. | Eutrophication<br>kg $PO_4^{3-}$ eq. | Global Warming<br>kg $CO_2$ eq. | Photochemical oxidation<br>kg $C_2H_4$ eq. | Ozone layer depletion<br>kg CFC-11 eq. | Abiotic depletion<br>kg Sb eq. | CED<br>MJ |
|---|---|---|---|---|---|---|---|
| 🟨 Upstream | 1.70E-02 | 2.45E-02 | 1.55E+00 | 8.04E-04 | 3.91E-07 | 1.10E-05 | 1.67E+01 |
| ■ Core | 5.44E-03 | 9.46E-04 | 1.03E+00 | 2.71E-04 | 1.73E-07 | 6.94E-08 | 1.66E+01 |
| 🟪 Downstream | 1.29E-04 | 5.92E-05 | 4.64E-02 | 8.66E-06 | 5.54E-09 | 5.05E-10 | 4.60E-01 |

**Figure 4. Environmental impacts of the dark chocolate life cycle assessed through CML-IA 2001 and CED split into upstream, core and downstream processes**

Given the obtained results, we deepened the analysis of the main unit processes included in the upstream and in the core phase (Table S.5 in the Supplementary material).

## 4.2. Upstream Process

The upstream processes involve the production of all the input materials required to manufacture the dark chocolate bars. The cultivation of *other* cocoa beans, imported from Dominican Republic and Uganda, causes the highest fractions on five of the seven impact categories considered. The production of inorganic fertilizers and pesticides generates 98% of total impact on AD, 63% on ODP, 25% on POC and 30% on CED (1.08E-05 kg $Sb_{eq.}$, 3.60E-07 kg CFC-$11_{eq.}$, 1.36E-04 kg $C_2H_{4eq.}$ per FU, and 9.98 MJ, respectively). The application of fertilizers and the related direct field emissions (i.e., nitrate, ammonia and nitrous oxide) mostly influence the EU, AC and GW categories (92%, 62%, and 42% of total impacts, respectively). The production of sugar causes the highest contributions to the photochemical oxidation category (35%) due to the carbon monoxide emissions from pre-harvest burning of sugar cane field. Finally, packaging has considerable fractions of impacts on global warming (13%, 0.37 kg $CO_{2eq.}$/FU), photochemical oxidation (13%, 0.14 $C_2H_{4eq.}$/FU) and acidification (10%, 2.3 g $SO_{2eq.}$/FU) due to heat and electricity required by packaging production process.

### 4.3. Core Process

Core processes include the transportation of the inputs to the production plant and chocolate manufacturing. A first remarkable cause of environmental impacts is the transportation of cocoa beans along global distances. The outcomes shown in Figure 5 highlight that the trans-oceanic ship transportation is responsible for about 14% of total acidification, mainly due to the sulfur dioxide emitted by ships. Cocoa beans transportation also generates 0.22 kg $CO_{2eq.}$/FU (9% of total GW) and 3.44 MJ (10% of total CED). Chocolate production is an energy consumptive process (Perez Neira, 2016; Vesce et al., 2016) and its contribution to total CED is 39% (13 MJ/FU), mostly from non-renewable sources (Figure S.2 in the Supplementary Materials). It generates 28% of total global warming: 0.58 kg $CO_{2eq.}$/FU (78% of the whole manufacturing, i.e. UP6-UP11) are associated with the trigeneration plant (UP7), while 0.16 kg $CO_{2eq.}$/FU are due to the rest of chocolate production (UP6, UP8, UP9, UP10, UP11). Moreover, the supply of natural gas consumed in the process causes a significant impact on ozone depletion: halon leakages from the methane transportation pipelines system generate, indeed, about 23% of impact on the category.

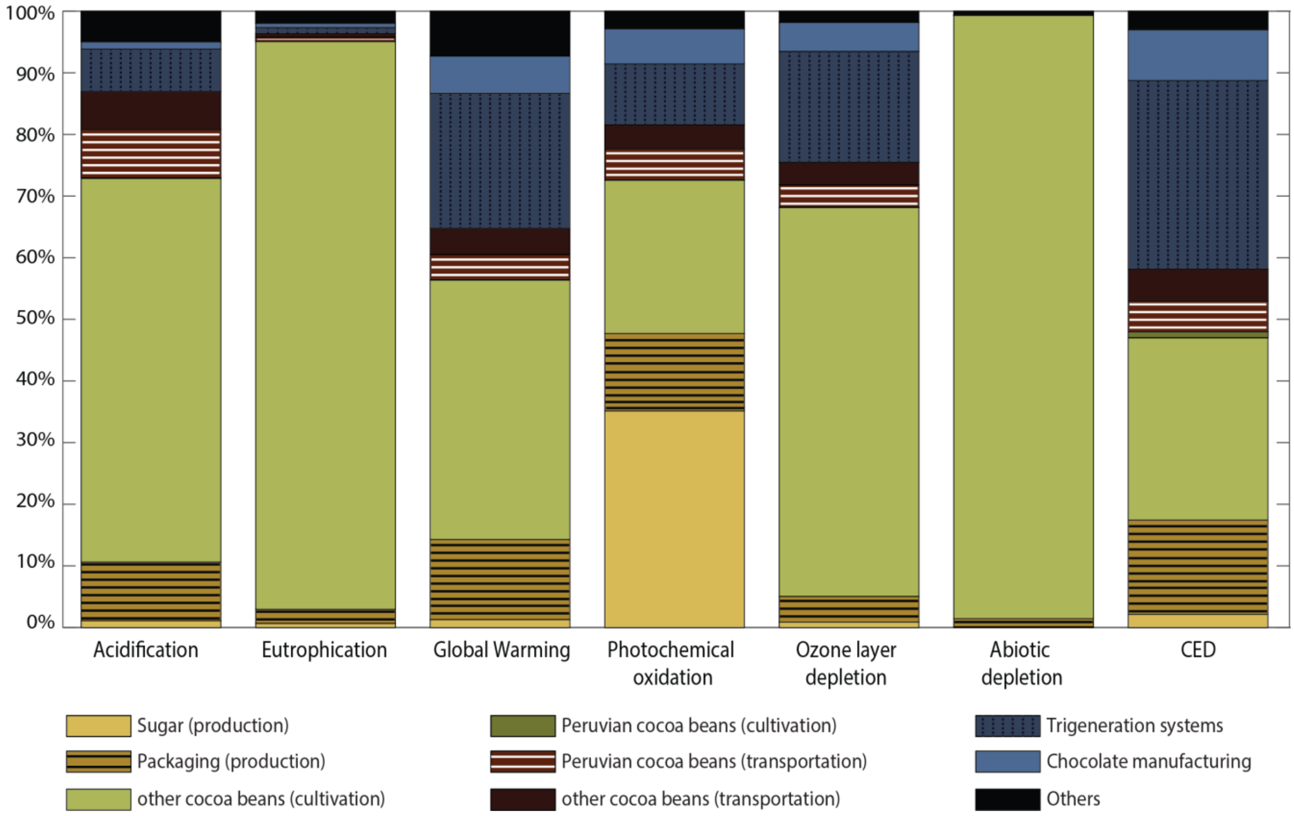


**Figure 5. Total impacts disaggregated into different unit processes. '*Others*' includes the production and transportation of jute and packaging, sugar transportation, and processes integrated in the downstream phase (i.e., distribution and EoL treatments). The impacts of this aggregated category ('*Others*') range from 1% to 7% on the AD and on the GW categories.**

## 5. LCA interpretation and sensitivity analysis

To support the results interpretation, we analyze the methodological assumption on cocoa shells allocation and we deepen the analysis of environmental hotspots emerged along the chocolate supply chain thanks to the LCA: the provisioning of cocoa beans (both the cultivation and the transportation to the production plant) and the energy supply at the manufacturing phase.

### 5.1. Cocoa Shells Allocation

In this study cocoa shells are considered as a "surplus" flow with a null allocation of environmental impacts (base scenario, BS). Nevertheless, cocoa shells can be sold to other companies for a further recovering of cocoa butter or for other purposes (Abiola and Tewe, 1991; International Cocoa Organization, 2003; Kouamé et al., 2011), eventually becoming a co-product, with a consequent application of allocation procedures in LCA. We thus compare the BS with an economic- and a mass-based allocation. Mass allocation factors ($\gamma_i$) are obtained from in-flows and out-flows of *RM* and *RMP* unit process, while the economic factors ($\lambda_i$) are based on economic values ($\delta_i$) of cocoa shells, cocoa powder, cocoa liquor and cocoa butter, which were provided as primary data by the company (Table S.6, Supplementary materials).

$$\gamma_i = \frac{m_i}{\sum_i m_i} \qquad \lambda_i = \frac{\delta_i m_i}{\sum_i \delta_i m_i} \tag{1}$$

From the obtained results (Figure S.3, Supplementary materials), it emerges that the *economic scenario* presents only a negligible reduction in chocolate impacts with respect to the *base scenario*, due to the small economic value of cocoa shells. On the other hand, the *mass scenario* entails a reduction of impacts ranging from 6.5% (on the global warming) to 12% (on the abiotic depletion).

### 5.2. Cocoa beans provisioning

The results obtained from LCI and LCIA highlighted the relevant contribution of cocoa beans provisioning to environmental impacts, as well as the high variability of environmental performances depending on the origins and type of cultivation (i.e., Peruvian vs. *other* cocoa beans). The cultivation of cocoa is located in tropical environments, from South America to tropical Africa and South-East Asia. Cocoa plantations range from the monoculture to the more complex agroforestry (Wood and Lass, 2008; Utomo et al., 2015) and are managed with extremely different practices (e.g., irrigated or rain-fed, different fertilizer types or dosages). Therefore, the magnitude of impacts on the environment and on the ecosystem services varies across plantations (Bartzas et al., 2017). As previously explained, the Italian company has provided primary data about the provisioning of the high-quality Peruvian cocoa beans (from mature cocoa plantation), while *other* cocoa beans have been modeled through Ecoinvent 3.3 database, assuming generic cocoa beans. Given the wide variety of cocoa origins and cultivations, this assumption needs a deeper investigation. We dedicated the sensitivity analysis to the 530 g of *other* cocoa beans, while the production of 590 g of Peruvian cocoa beans remains constant, because they are the peculiar feature of the dark chocolate under study and cannot be modified. We compare alternative cocoa beans provisioning scenarios defined through the Ecoinvent 3.3 database, which provides data about four types of cocoa beans from different areas of the world (Ivory Coast ‘CI’, Ghana ‘GH’, Indonesia ‘ID’, and Rest-of-the-World which is Base Scenario in this study ‘BS’), managed with different practices (e.g., ID is rain-fed and intensively fertilized, while GH is irrigated and lower fertilized). Besides cocoa cultivation, the travelling distance from the cultivation site to the chocolate manufacturing plant increases from 6,982 km in the case of Ghanaian and Ivorian cocoa to more than 11,500 km in the cases of Peruvian (11,823 km) and Indonesian (12,032 km) ones. The four scenarios (BS, CI, GH and ID) are compared through the CML-IA 2001 impact assessment method and CED indicator.

The results, reported in Figure 6 (axis labels), show that a different choice in the cocoa provisioning can significantly reduce the environmental impacts of the whole chocolate life cycle from -5% (ODP) to -69% (EU). The production of cocoa beans in Indonesia (ID) generates the highest impacts on the majority of the categories, mainly due to the direct field emissions caused by the large use of fertilizers. For instance, nitrous oxide emissions cause 55% on the total GW, ammonia 71% on the AC and nitrate 81.2% on the EU categories (see Table S.7 in the Supplementary Materials). The same field emissions also represent significant fractions in the CI scenario: 48.1% of AC, 73% of EU and 36.5% of GW. Different outcomes are obtained for Ghanaian cultivation, in which the most relevant contributions to GW, AC and CED (51%, 30% and 62%, respectively) are due to the facilities used for the irrigation of plantation. Specifically, the value of CED (35 MJ/FU) is 1.1 MJ/FU higher than ID and 4 MJ/FU than CI.

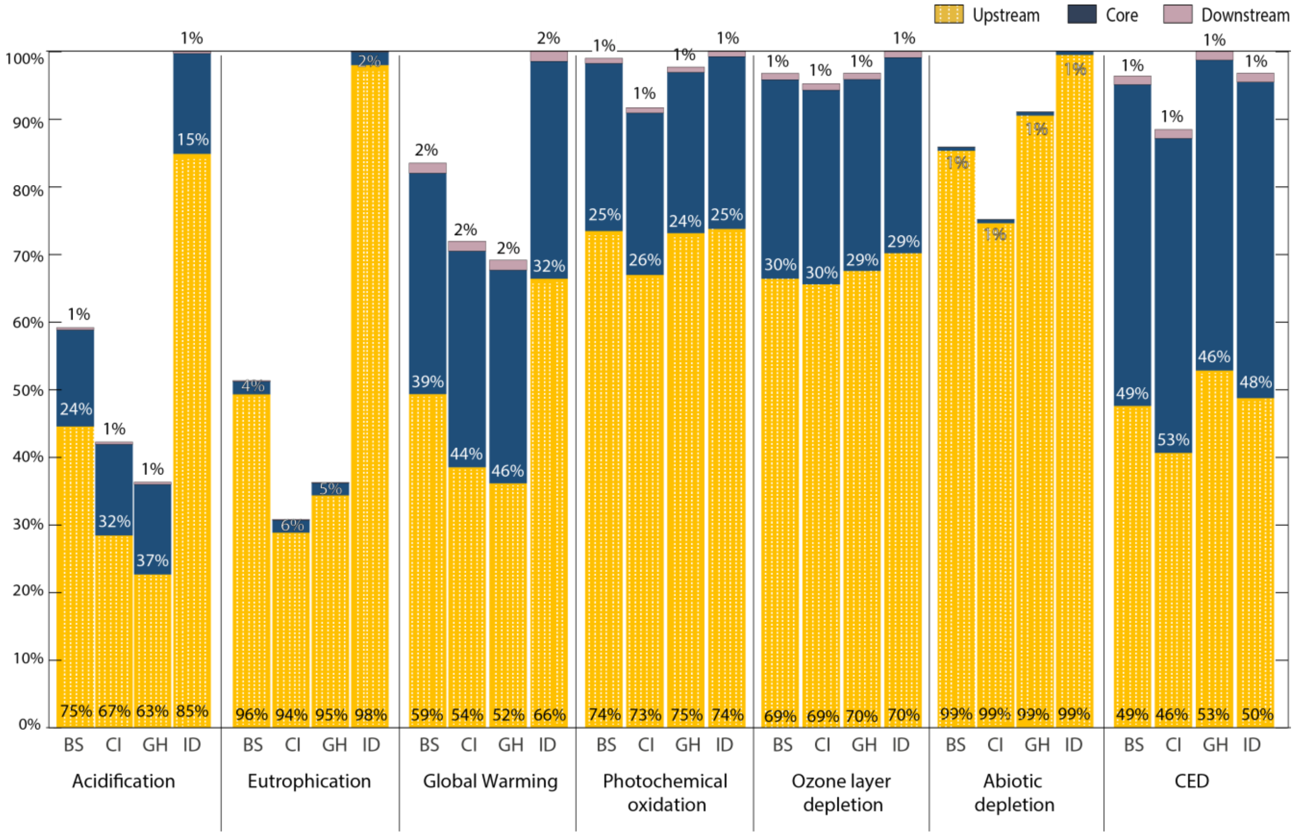


**Figure 6. Comparison of the environmental impacts of the whole life cycle of 1 kg of dark chocolate assuming four different cocoa provisioning scenarios (100% is the worst scenarios, the one with the highest impacts) according to the split into upstream, core and downstream processes. Axis labels refer only to the total impact value of the scenarios with respect to the worst, while the breakdown of each scenario is represented with the labels in the histogram columns. [BS: Base Scenario; CI: Ivory Coast; GH: Ghana; ID: Indonesia]**

Besides the variations in total values, also the breakdown of impacts between upstream, core and downstream differs in the four scenarios (Figure 6, labels in the columns). For instance, the upstream contribution to the total value of global warming increases from 52% in the GH scenario to 66% in the ID scenario, while the contribution to the total value of acidification ranges from 63% for GH to 85% in the ID case. Since the selected categories do not assess the environmental impacts caused by the application of pesticides, a preliminary assessment on human toxicity and eco-toxicity categories (fresh water eco-toxicity, marine eco-toxicity and terrestrial eco-toxicity) is carried out through the CML-IA 2001 method. The results described in section S.2.2.3 (Supplementary materials) show that cocoa beans from Indonesia have the highest impacts on three of the four toxicity categories, i.e., human, freshwater and terrestrial eco-toxicity, while GH scenario causes the highest impact on marine eco-toxicity.

This preliminary sensitivity analysis highlights the importance of the agricultural and transportation phases of cocoa beans in the assessment of chocolate life cycle, confirming recently published outcomes about permanent cultures (Bartzas et al., 2017) and variability of agroecosystems (Notarnicola et al., 2017).

### 5.3. Energy

The LCA results show that the energy-intensive chocolate manufacturing causes a relevant fraction of the global warming impact category (about 22% of the total). The Italian chocolate company is equipped with a recently renovated and efficient production plant based on a trigeneration system including the best technologies available on the market. In order to investigate possible environmental benefits guaranteed by this efficient energy supply system, we compared it with the Italian scenario, i.e., the required electricity, thermal and cooling energy are supplied by the Italian national grid (Ecoinvent 3.3 database). Results reported in Figure 7 show that the trigeneration system enables to reduce impacts from -25% to -91%, on the global warming and on the abiotic depletion categories, respectively. This improvement is mainly due to the usage of natural gas instead of the hard coal and oil, which characterizes the Italian energetic mix. The only exception regards the ozone layer depletion category, where an increase of about 8% is due to the leaks of halon gas along the supply chain of natural gas.

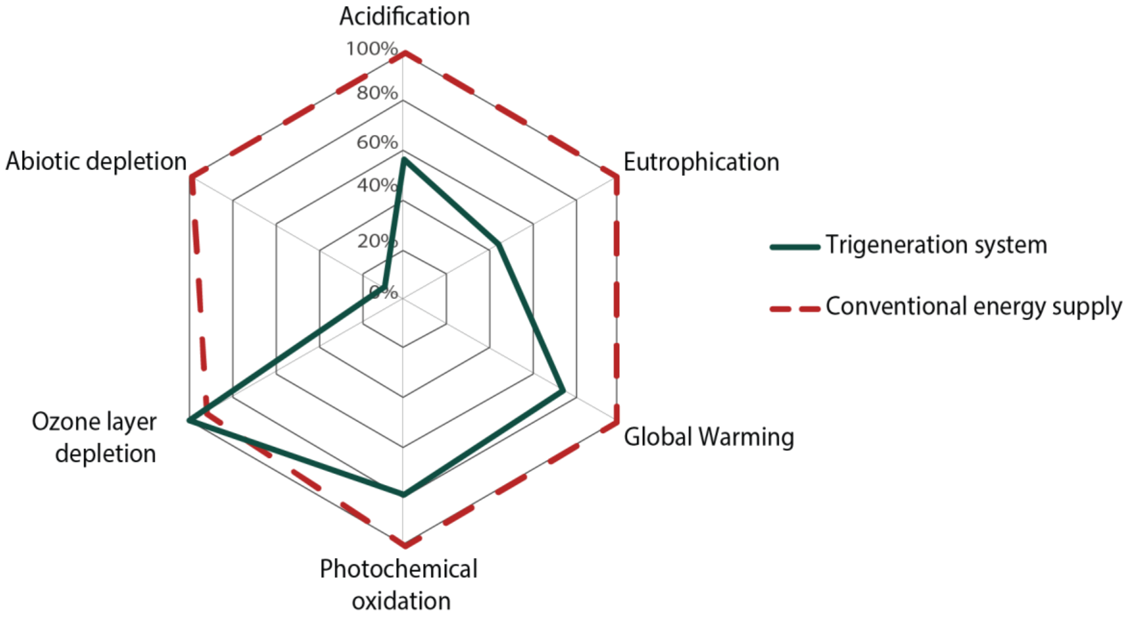


**Figure 7. Comparison of environmental impacts due to two different energy supply scenarios, i.e., trigeneration and conventional energy supply**

The results of CED are separately reported to highlight the contributions of non-renewable and renewable energy. Figure 8 shows that the total cumulative energy demand increases from 33.75 MJ/FU of base scenario to 36.75 MJ/FU (+9 %) with conventional energy supply. Focusing on the renewable resources, the conventional energy supply is characterized by a fraction of 6.2% guaranteed by the Italian national mix, while in the base scenario it is reduced to 4% due to the use of natural gas.

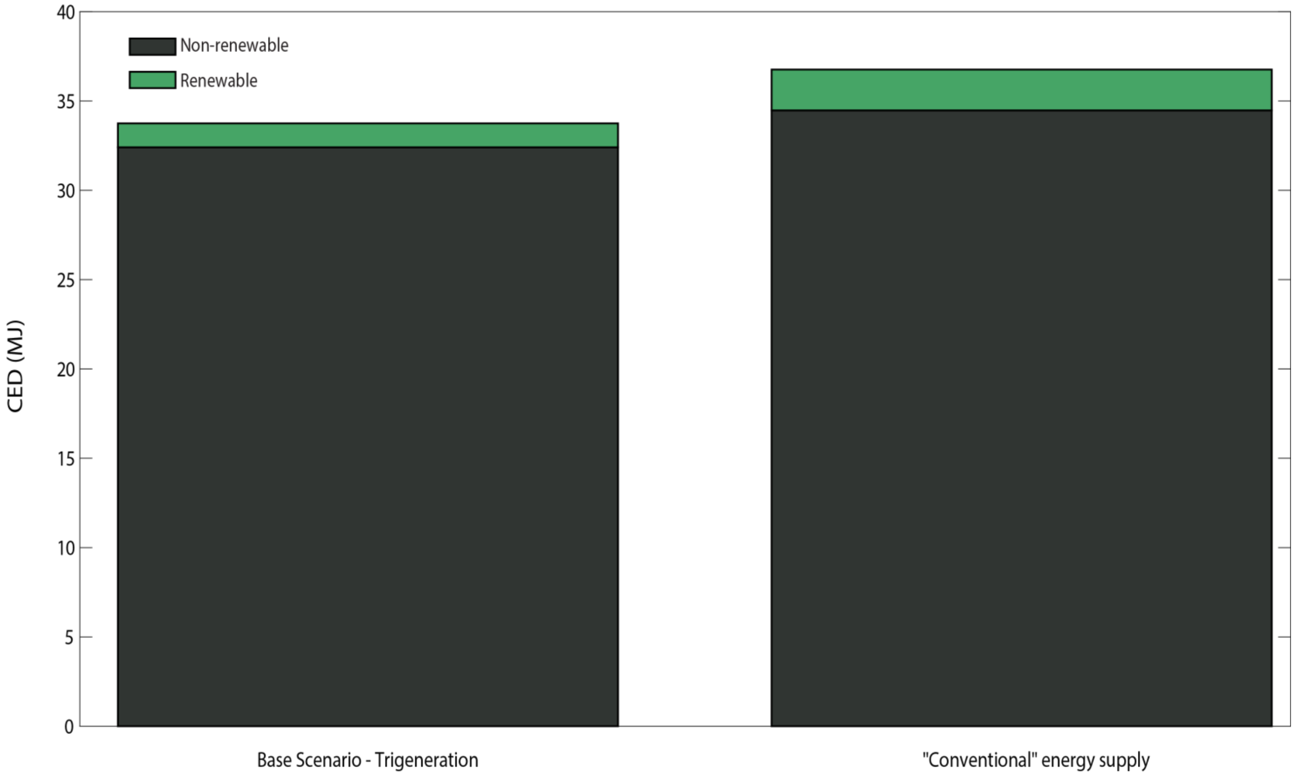


**Figure 8. Sensitivity analysis on energy provisioning in terms of CED (MJ): comparison between an energy supply system based on a trigeneration system and a system based on the average Italian market**

## 6. Discussion and conclusions

Despite the increasing interest in environmental sustainability of the agri-food sector, environmental assessments and certifications of chocolate and other cocoa derivatives are still missing (Figure 2). Given this lack and the increasing global demand for cocoa-derivative products, complete environmental assessments are fundamental to support chocolate producers in improving the environmental sustainability of their production. To this aim, we perform a *cradle-to-grave* LCA of an Italian dark chocolate mainly based on primary data. Our primary objectives are (i) the identification of the environmental hotspots along the chocolate supply chain and (ii) the assessment of possible alternative scenarios. The outcomes obtained through the CML-IA 2001 method are in line with the studies available in the literature. For instance, the resulting global warming of 2.62 kg $CO_{2eq.}$ per FU is comparable to the values reported in Büsser and Jungbluth (2009) (2.1 kg $CO_{2eq.}$) and Perez Neira (2016) (2.57 kg $CO_{2eq.}$). Referring to the different phases of the chocolate life cycle, upstream and core processes cause the highest fractions of the considered impact categories. Specifically, the production of raw materials has the highest impacts on abiotic depletion, eutrophication and photochemical oxidation, while cocoa beans transportation and packaging production considerably contribute to global warming, CED and photochemical oxidation. The obtained result on global warming category due to cocoa transportation (0.22 kg $CO_{2eq.}$ per kg of beans) is within the same order of magnitude of those obtained in Perez Neira et al. (2014) and Perez Neira (2016) (from 0.22 to 0.39 kg $CO_{2eq.}$). In addition, packaging production (0.34 kg $CO_{2eq.}$/FU) falls within the range between 0.28 and 1.91 kg $CO_{2eq.}$ per FU reported by Allione and Petruccelli (2012) and Perez Neira (2016). Finally, although the chocolate manufacturing is an optimized and efficient industrial process, it generates relevant impacts on global warming, ozone layer depletion, and CED due to energy requirements. Considering the overall core phase (transportation and manufacturing) together with the packaging production, our results (1.37 kg $CO_{2eq.}$ and 1.97E-07 kg CFC-$11_{eq.}$) are again in line to the ones found in existing literature: Vesce et al. (2016) reports 1.91 kg $CO_{2eq.}$ for global warming and 2.34E-07 kg CFC-$11_{eq.}$ for ozone layer depletion[3].

From the LCIA results, cocoa bean provisioning (i.e., cultivation and transportation) and energy supply at the manufacturing plant have emerged as environmental hotspots along the chocolate supply chain. Therefore, their investigation is deepened through a sensitivity analysis. The comparison of different scenarios of cocoa cultivation and origin confirms (i) the relevance of the environmental impacts caused by the agricultural phase (Roy et al., 2009) with respect to the whole life cycle, and (ii) the influence of agricultural ecosystems and practice variability on the environmental impacts (Notarnicola et al., 2017). Secondly, the in-depth analysis of energy supply for cocoa beans transformation allows to quantitatively assess the environmental benefits guaranteed by an efficient energy supply system, like the trigeneration plant, in comparison with a conventional energy supply.

---

[3] It is important to point out that in the present study the roasting phase of raw cocoa beans is included in the manufacturing process, whereas it is outside system boundaries in Vesce et al. (2016).

The proposed methodology and system modelling, together with the obtained outcomes (both LCI and LCIA and in-depth analysis) could support chocolate companies in assessing the environmental profile of their products and in taking strategic decisions to improve their environmental sustainability, like changing raw materials and/or the type of energy supply. For instance, if a company would decide to satisfy its cocoa demand only with Peruvian cocoa beans, it would consistently reduce its environmental impacts (i.e., from -42% for the POC up to -99% for AD and EU) with respect to a provisioning based on the Indonesian cocoa (Figure S.4, Supplementary materials). Further developments are required to improve the investigation of the agricultural phase (i.e. the collection of primary data and estimation of direct field emissions), to enlarge the evaluation to other environmental impact categories (e.g., water consumption, carbon balance between land-use change and relative $CO_2$ emissions and plantation storage, energy embedded in plantation) and to create a comprehensive methodological framework for the comparison of chocolate with other food and beverages (e.g., festive bread, beer, wine) under a nutritional, sensorial, cultural and social perspective (Rousseau, 2015; Notarnicola et al., 2016, 2017).

## Acknowledgments

The authors thank the ICAM S.p.A staff, and especially Eng. Antonello Ercole, for the constant support to this research, from the data collection to results discussion.

## Bibliography

Abiola, S.S., Tewe, O.O., 1991. Chemical evaluation of cocoa by-products. Trop. Agric. 68, 335–336.

Allione, C., Petruccelli, L., 2012. A Multicriteria Method for Assessing the Eco- performances of Food Packing. 2nd World Sustainability Forum. Avaiable on Webside: www.wsforum.org (accessed 30.08.17.).

Barona, E., Ramankutty, N., Hyman, G., Coomes, O.T., 2010. The role of pasture and soybean in deforestation of the Brazilian Amazon. Environ. Res. Lett. 5, 024002. doi:10.1088/1748-9326/5/2/024002

Bartzas, G., Komnitsas, K., 2017. Life cycle analysis of pistachio production in Greece. Sci. Total Environ. 595, 13–24. doi:10.1016/j.scitotenv.2017.03.251

Bessou, C., Basset-Mens, C., Tran, T., Benoist, A., 2013. LCA applied to perennial cropping systems: a review focused on the farm stage. Int. J. Life Cycle Assess. 18, 340–361.

doi:10.1007/s11367-012-0502-z

Bonamente, E., Scrucca, F., Rinaldi, S., Merico, M.C., Asdrubali, F., Lamastra, L., 2016. Environmental impact of an Italian wine bottle: Carbon and water footprint assessment. Sci. Total Environ. 560-561, 274–283. doi:10.1016/j.scitotenv.2016.04.026

Buratti, C., Fantozzi, F., Barbanera, M., Lascaro, E., Chiorri, M., Cecchini, L., 2017. Carbon footprint of conventional and organic beef production systems: An Italian case study. Sci. Total Environ. 576, 129–137. doi:10.1016/j.scitotenv.2016.10.075

Büsser, S., Jungbluth, N., 2009. LCA of Chocolate Packed in Aluminium Foil Based Packaging. ESU-services.

CiAl (Consorzio imballaggi Alluminio), 2014. Annual Report.

Comieco (Consorzio Nazionale Recupero e Riciclo degli imballaggi a base Cellulosica), 2015. 20° Rapporto.

EcoTransIT, 2014. EcoTransIT World - a sustainable move. URL: http://www.ecotransit.org/index.it.html (accessed 1.13.17).

FAO, 2011. The State of the World's Land and Water Resources for Food and Agriculture. Managing Systems at Risk. Lancet 2, 285. doi:10.4324/9780203142837

FAO, 2016. AQUASTAT website. URL: http://www.fao.org/nr/water/aquastat/water_use/index.stm

FAO, 2017. FAOSTAT. URL: www.fao.org/faostat (accessed 6.05.17).

Frischknecht, R.; Jungbluth, N.; Althaus, H.J.; Doka, G.; Dones, R.; Hischier, R.; Hellweg, S.; Humbert, S.; Margni, M.; Nemecek, T.; Spielmann, M. 2007. Implementation of Life Cycle Impact Assessment Methods: Data v3.3. ecoinvent report No. 3, Swiss centre for Life Cycle Inventories, Dübendorf, Switzerland

Guinée, J.B., 2002. Handbook on life cycle assessment: operational guide to the ISO standards / Jeroen B. Guinée (final editor), Eco-efficiency in industry and science. Ecomed. doi:10.1007/BF02978897

Heijungs, R., 1992. Nordic Guidelines on Life-Cycle Assessment.

Huijbregts, M.A.J., Rombouts, L.J.A., Hellweg, S., Frischknecht, R., Hendriks, J.A., Van de Meent, D., Ragas, A. m J., Reijnders, L., Struijs, J., 2006. Is Cumulative Fossil Energy Demand a Useful Indicator for the Environmental Performance of Products? Environ. Sci. Technol. 40, 641–648. doi:10.1021/es051689g

International Cocoa Organization, 2003. Products that can be made from cocoa. Int. Cocoa Organ. URL https://www.icco.org/faq/52-by-products/115-products-that-can-be-made-from-cocoa.html (accessed 12.17.16).

International EPD System, 2014. Product Category Rules -Refined Sugar From Sugar Beet 1–16.

International EPD System, 2015a. General Programme Instruction for the International EPD® System (version 2.5).

International EPD System, 2015b. Product category Rules - Bakery Products 1–32.

International EPD System, 2016. URL: https://www.environdec.com.

IPCC, 2006. IPCC Guidelines for National Greenhouse Gas Inventories. Volume 4: Agriculture, forestry and other land use.

ISO, 2006a. ISO 14040:2006 Environmental Management - Life Cycle Assessment - Principles and Framework.

ISO, 2006b. ISO 14044:2006 Environmental Management - Life Cycle Assessment - Principles and Framework.

ISO, 2006c. ISO 14025:2006 Environmental labels and declarations - Type III environmental claims.

Jacobi, J., Andres, C., Schneider, M., Pillco, M., Calizaya, P., Rist, S., 2014. Carbon stocks, tree diversity, and the role of organic certification in different cocoa production systems in Alto Beni, Bolivia. Agrofor. Syst. 88, 1117–1132. doi:10.1007/s10457-013-9643-8

Kastner, T., Rivas, M.J.I., Koch, W., Nonhebel, S., 2012. Global changes in diets and the consequences for land requirements for food. Proc. Natl. Acad. Sci. U. S. A. 109, 6868–72. doi:10.1073/pnas.1117054109

Kouamé, B., Marcel, G., André, K.B., Théodore, D., Bouafou, A., Guy, K., Agr, I.J., Agri, R., 2011. Waste and by-products of cocoa in breeding : Research synthesis. Int. J. Agron. Agric. Res. 1, 9–19.

Moss, B., 2008. Water pollution by agriculture. Philos. Trans. R. Soc. Lond. B. Biol. Sci. 363, 659–66. doi:10.1098/rstb.2007.2176

Neira, D. P., Fernández, X. S., Rodríguez, D. C., Montiel, M. S., & Cabeza, M. D. (2016). Analysis of the transport of imported food in Spain and its contribution to global warming. Renewable Agriculture and Food Systems, 31(1), 37-48.

Notarnicola, B., Tassielli, G., Renzulli, P.A., Castellani, V., Sala, S., 2016. Environmental impact of food consumption in Europe. J. Clean. Prod. 140 (part-2), 753e765. http://dx.doi.org/10.1016/j.jclepro.2016.06.080.

Notarnicola, B., Sala, S., Anton, A., McLaren, S.J., Saouter, E., Sonesson, U., 2017. The role of life cycle assessment in supporting sustainable agri-food systems: A review of the challenges. J. Clean. Prod. 140, 399–409. doi:10.1016/j.jclepro.2016.06.071

Ntiamoah, A., Afrane, G., 2008. Environmental impacts of cocoa production and processing in Ghana: life cycle assessment approach. J. Clean. Prod. 16, 1735–1740. doi:10.1016/j.jclepro.2007.11.004

Perez Neira, D., 2016. Energy sustainability of Ecuadorian cacao export and its contribution to climate change. A case study through product life cycle assessment. J. Clean. Prod. 112, 2560–2568. doi:10.1016/j.jclepro.2015.11.003

Rajab, Y.A., Leuschner, C., Barus, H., Tjoa, A., Hertel, D., 2016. Cacao cultivation under diverse shade tree cover allows high carbon storage and sequestration without yield losses. PLoS One 11, e0149949. doi:10.1371/journal.pone.0149949

Recanati, F., Allievi, F., Scaccabarozzi, G., Espinosa, T., Dotelli, G., Saini, M., 2015. Global Meat Consumption Trends and Local Deforestation in Madre de Dios: Assessing Land Use Changes and other Environmental Impacts. Procedia Eng. 118, 630–638. doi:10.1016/j.proeng.2015.08.496

Rousseau, S., 2015. The role of organic and fair trade labels when choosing chocolate. Food Qual. Prefer. 44, 92–100. doi:10.1016/j.foodqual.2015.04.002

Roy, P., Nei, D., Orikasa, T., Xu, Q., Okadome, H., Nakamura, N., Shiina, T., 2009. A review of life cycle assessment (LCA) on some food products. J. Food Eng. 90, 1–10. doi:10.1016/j.jfoodeng.2008.06.016

Silva, A.R. de A., Bioto, A.S., Efraim, P., Queiroz, G. de C., 2017. Impact of sustainability labeling in the perception of sensory quality and purchase intention of chocolate consumers. J. Clean. Prod. 141, 11–21. doi:10.1016/j.jclepro.2016.09.024

Smith, P., Bustamante, M., Ahammad, H., Clark, H., Dong, H., Elsiddig, E.A., Haberl, H., Harper, R., House, J., Jafari, M., Masera, O., Mbow, C., Ravindranath, H.N., Rice, C.W., Abad Robledo, C., Romanovskaya, A., Sperling, F., Tubiello, F., 2014. Agriculture, Forestry and Other Land Use (AFOLU)., in: Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge.

Solazzo, R., Donati, M., Tomasi, L., Arfini, F., 2016. How effective is greening policy in reducing GHG emissions from agriculture? Evidence from Italy. Sci. Total Environ. 573, 1115–1124. doi:10.1016/j.scitotenv.2016.08.066

Statista, The statistics portal. Retail consumption of chocolate confectionery worldwide from 2012/13 to 2018/19. https://www.statista.com/statistics/238849/global-chocolate-consumption/ (accessed 16.06.17).

Tilman, D., Clark, M., 2014. Global diets link environmental sustainability and human health. Nature 515, 518–522. doi:10.1038/nature13959

Utomo, B., Prawoto, A.A., Bonnet, S., Bangviwat, A., Gheewala, S.H., 2015. Environmental performance of cocoa production from monoculture and agroforestry systems in Indonesia. J. Clean. Prod. 1–9. doi:10.1016/j.jclepro.2015.08.102

Vesce, E., Olivieri, G., Pairotti, M.B., Romani, A., Beltramo, R., 2016. Life cycle assessment as a tool to integrate environmental indicators in food products : a chocolate LCA case study. Int. J. Environ. Heal. 8, 21–37. doi:10.1504/IJENVH.2016.077660

Wernet, G., Bauer, C., Steubing, B., Reinhard, J., Moreno-Ruiz, E., Weidema, B., 2016. The ecoinvent database version 3 (part I): overview and methodology. Int. J. Life Cycle Assess. 21, 1218–1230. doi:10.1007/s11367-016-1087-8

Wood, G. A. R., & Lass, R. A. (2008). *Cocoa*. John Wiley & Sons.

# From beans to bar: a Life Cycle Assessment towards sustainable chocolate supply chain

Francesca Recanati[a]*, Davide Marveggio[b], Giovanni Dotelli[c]

[a] Dipartimento di Elettronica, Informazione e Bioingegneria, Politecnico di Milano, via Ponzio 34/5, 20133, Milano, Italy

[b] Dipartimento di Scienze Agrarie e Ambientali - Produzione, Territorio, Agroenergia, Università degli studi di Milano, via Celoria 2, 20133, Milano, Italy

[c] Dipartimento di Chimica, Materiali e Ingegneria Chimica "G. Natta", Politecnico di Milano, Piazza Leonardo da Vinci 32, 20133 Milano, Italy

* Corresponding author. Tel.: +390223994030; fax: +390223993412

*E-mail address:* francesca.recanati@polimi.it (F. Recanati).

## Abstract

The environmental sustainability has emerged as a crucial aspect in the agri-food sector, nevertheless environmental assessments and certifications of cocoa and chocolate are still missing. Given this gap and the increasing global demand for cocoa derivatives, this study aims to evaluate the environmental impacts of an Italian dark chocolate through a holistic *cradle-to-grave* Life Cycle Assessment (LCA). The impact categories assessed are acidification potential (AC), eutrophication potential (EU), global warming potential (GW), photochemical ozone creation potential (POC), ozone layer depletion potential (OD), abiotic depletion (AD) and cumulative energy demand (CED). The obtained results highlight the relevant contributions of upstream phase (63% for the ODP, 92% for EU and 99% for the AD) and core processes (39% for the GW and 49% for the CED) on the overall impacts. Specifically, cocoa provisioning and energy supply at the manufacturing plant emerged as environmental hotspots and have been deeper investigated through a sensitivity analysis. Obtained outcomes show the significant variability of the environmental impacts due to the agricultural phase (i.e., depending on agroecosystems and practices) and environmental benefits guaranteed by an efficient trigeneration system implemented in the manufacturing plant. The quantification of the environmental impacts of chocolate through LCA, the identification of the main hotspots along the supply chain and the sensitivity analysis performed in this study could effectively support chocolate companies in their pathway towards environmentally sustainable productions.

## Keywords

Chocolate, Agri-food sector, Environmental sustainability, Life Cycle Assessment, Chocolate manufacturing, Environmental labeling

# 1. Introduction

The environmental sustainability has been emerging as a pivotal aspect in the agri-food sector. Food production is responsible for more than 25% of global greenhouse gas emissions (Tilman and Clark, 2014; Solazzo et al., 2016), it bears a large share of responsibility for water consumption and contamination (Moss, 2008; Smith et al., 2014; FAO, 2016) and it uses about a half of ice-free land area on Earth as cropland and pasture (FAO, 2011; Kastner et al., 2012), which are often created through deforestation (Barona et al., 2010; Recanati et al., 2015). The chocolate supply chain is characterized by global geographical boundaries. The agricultural production of cocoa is located in tropical areas (Jacobi et al., 2014; Utomo et al., 2015) of Africa, Asia and Americas (FAO, 2017), often contributing, at least in the past, to deforestation. Once cocoa beans are harvested, fermented and dried, they are exported to major chocolate producer countries located in the temperate band like Europe and Northern America (Perez Neira, 2016). At the manufacturing plant, a complex industrial transformation takes place in order to obtain derivative products like chocolate, cocoa powder and butter. The global demand for cocoa derivatives and chocolate has tripled since the sixties and an increment of about +91% has been registered in the last 20 years (Figure 1) (FAO, 2017). Specifically, from 90's Asian and African countries showed an increase of cocoa supply of +337% and +894%, respectively (FAO, 2017). Despite this recent increment, the per-capita consumption in Asian and African countries remains far below the global average and this further emphasizes the growth in demand of cocoa derivatives forecasted for the forthcoming years (www.statista.com).

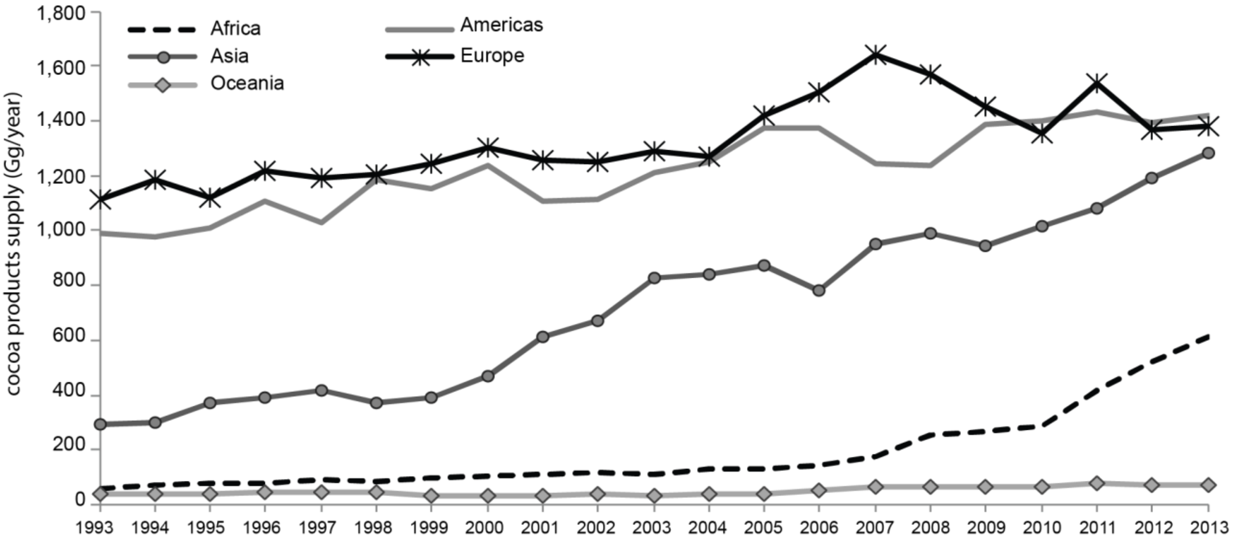


**Figure 1. Cocoa products supply statistics for the five continents (1993-2013) (FAO, 2017)**

Given the growing attention to food-related environmental impacts, food companies showed a large and active participation in environmental research and labeling (International EPD System, 2016; Bonamente et al., 2016; Buratti et al., 2017). In the last decade, the cocoa sector showed an increase in organic and fair trade certifications highlighting efforts in the environmental and social spheres (Silva et al., 2017). Nevertheless, neither environmental certifications based on quantitative assessment like the Environmental Product Declaration by the International EPD® System (International EPD System, 2016) nor the related Product Category Rules (PCRs) (ISO, 2006c) currently exist for this sector. In the literature, the environmental dimension of cocoa and chocolate supply chain has been partially investigated (Bessou et al., 2013) and, to the authors' knowledge, no studies have performed a cradle-to-grave and multiple environmental indicators Life Cycle Assessment. For instance, existing studies (Figure 2) analyzed the whole life cycle of chocolate focusing on specific environmental impacts, such as global warming and energy demand (Perez Neira, 2016), while others focused on specific life-cycle steps, like the cocoa beans production (Jacobi et al., 2014; Utomo et al., 2015; Rajab et al., 2016; Ntiamoah and Afrane, 2008) or the chocolate manufacturing (Vesce et al., 2016).

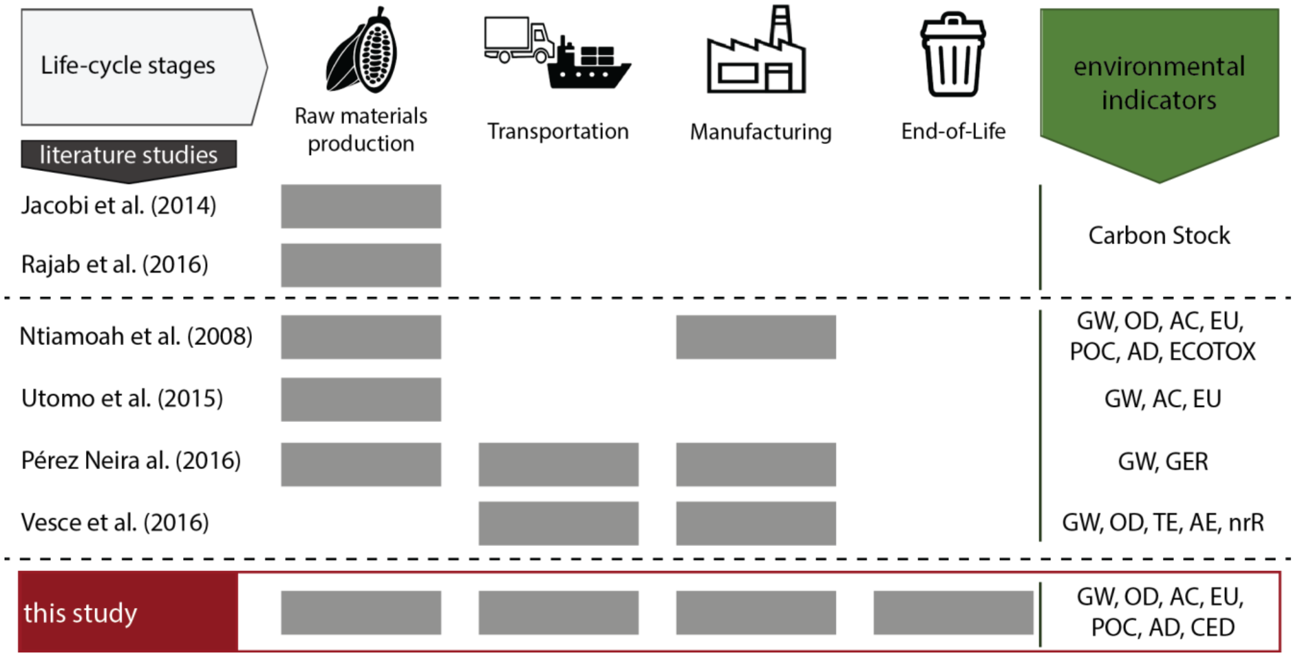


**Figure 2. State of the art about the environmental assessment of cocoa and chocolate production. For each analyzed study we highlighted the life-cycle stages involved and the environmental indicators. Grey rectangles indicate that the life-cycle stage (column heading) is considered in the study (row heading). On the right side of the figure we reported the assessed environmental indicators (GW: Global Warming, GER: Gross Energy Requirement, OD: ozone depletion layer, TE: Terrestrial Eco-toxicity, AE: Aquatic Eco-toxicity, nrR: non-renewable primary resources, AC: Acidification, EU: Eutrophication, POC: Photo-Chemical Oxidation, AD: Abiotic Depletion, , ECOTOX: Freshwater-, Human- and Terrestrial eco-toxicity; CED: Cumulative Energy Demand). In the last row, we reported the information related to the present study.**

Given the continuous increase in cocoa derivatives demand and the existing literature gap, further studies are fundamental to support chocolate producers in assessing, and eventually improving, the environmental sustainability of their production. This study gives a contribution to this issue by assessing the environmental performances of a dark chocolate with the aim of highlighting the main environmental hotspots along the entire supply chain. This is accomplished through two main steps. Firstly, a *cradle-to-grave* LCA is performed according to the ISO 14040–14044 (ISO, 2006a, 2006b). A detailed inventory was created in collaboration with an Italian company characterized by a recently renovated production plant. The data survey covered the whole supply chain, with a detailed focus on the manufacturing stage. In the second part of the study, a sensitivity analysis is performed to evaluate the influence of alternative scenarios of the life cycle phases, which emerged as environmental hotspots from the LCA results.

## 2. Materials and Methods

The environmental impacts of dark chocolate are assessed through the LCA, a methodology that observes and analyses a product over its entire life cycle (ISO, 2006a, 2006b). In the following sections, all the LCA stages (i.e., goal and scope definition, Life Cycle Inventory or LCI, Life Cycle Impact Assessment or LCIA, and interpretation of results) are performed.

## 2.1. Goal and scope definition

The goal of this LCA is to assess the environmental impacts of an Italian dark chocolate adopting a *cradle-to-grave* approach.

### 2.1.1. Dark chocolate characterization

The main ingredients composing the dark chocolate under study are cocoa liquor from Peruvian cocoa beans (50.1%), and butter and powder, both from cocoa beans with unspecified origins (referred to as *other* cocoa beans from now on) (Table 1). Every bar is wrapped into an aluminum foil (1.8 g) and a cardboard (11.8 g). Finally, the production site is located in northern Italy.

**Table 1. Recipe and packaging of the Italian dark chocolate bar (100 g)**

| Ingredients | Percentage |
|---|---|
| Cocoa Liquor | 50.1% |
| Cocoa Butter | 20.2% |
| Sugar | 13.7% |
| Cocoa Powder | 16.0% |
| Vanilla Extract | <0.1% |
| **Packaging** | **Mass** |
| Aluminum Foil | 1.8 g |
| Cardboard | 11.8 g |

### 2.1.2. Functional Unit and System Boundaries

The Functional Unit (FU) analyzed is 1 kg of dark chocolate (corresponding to 10 bars of 100 g) and the relative packaging. Figure 3 shows the system boundaries and the unit processes composing the production system, grouped into upstream, core and downstream processes (International EPD

System, 2015a). Since no PCRs exist for cocoa and its derivatives, the methodological approach followed in this study has been developed according to existing PCRs of other food commodities. Specifically, the system boundaries and the division into upstream, core and downstream followed the PCR of sugar (”*Refined sugar from sugar beet”,* UN CPC 234).

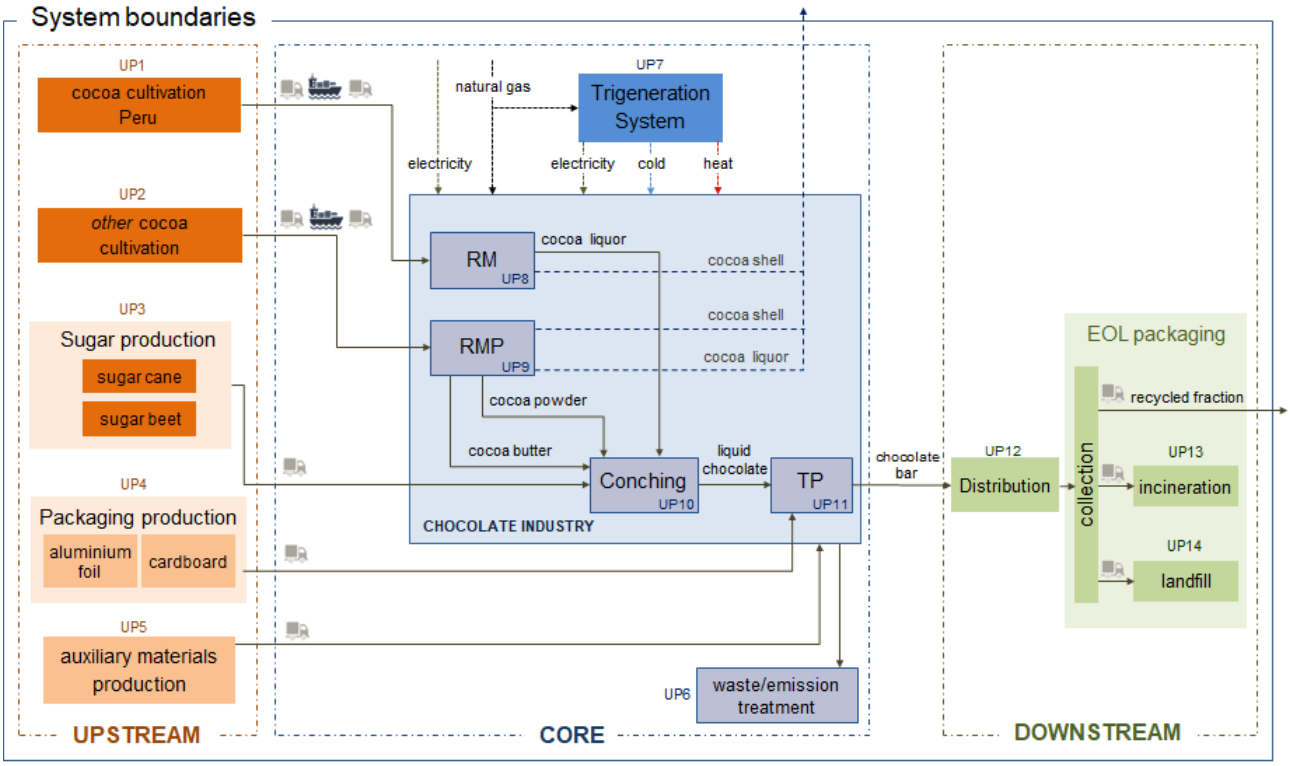


**Figure 3. Production process scheme and system boundaries of the LCA of 1 kg of dark chocolate (RM:** ***Roasting and milling;*** **RMP:** ***roasting, milling and pressing;*** **Conching:** ***mixing, refining and conching;*** **TP:** ***tempering, molding, cooling and packing*****; EOL;** ***end-of-life).***

The main unit processes are here briefly described following the upstream, core and downstream partitioning (see Table 2 for a summary). Upstream processes comprehend the production of raw cocoa, other ingredients (e.g., sugar cane and sugar beet), packaging (i.e., cardboards and aluminum foils) and auxiliary materials required by the production process (e.g., lubricant oil, detergent, jute). Core processes include the transportation of all the aforementioned inputs from the respective production sites to the chocolate factory in northern Italy, the manufacturing of dark chocolate and the treatment of industrial waste. Within the manufacturing site, cocoa beans are winnowed, pre-roasted to separate cocoa shells and, then, chipped. Consequently, two alternative processes can be performed to convert cocoa beans into derivatives: the *roasting and milling* unit (*RM*, UP8) transforms Peruvian cocoa beans into cocoa liquor, whereas the *roasting, milling and pressing* unit (*RMP*, UP9) transforms *other* cocoa beans into either cocoa liquor, cocoa powder or butter. The UP10 includes the mixing of chocolate ingredients (Peruvian cocoa liquor, cocoa butter, sugar, and cocoa paste), the subsequent refining, and the conching process. The obtained liquid chocolate is tempered (*TP*), i.e., is thermally treated to become hard, durable and melty at body temperature. One kilogram of tempered chocolate is poured into molds and, once cooled, it is wrapped into an aluminum foil and in a cardboard (UP11). The majority of energy required by the chocolate manufacturing is supplied by a methane-powered trigeneration system (UP7) installed in the factory. Electricity, thermal and cold energy correspond to 50%, 35.4% and 14.6% of its total energy out-flow, respectively. Avoided impacts are not accounted for energy produced by the trigeneration plant (i.e., electricity, heat and cold). Besides the trigeneration system, the national grid satisfies further energy requirements (both electricity and natural gas). Finally, downstream processes include the distribution of chocolate, the collection of packaging waste and its End-of-Life (EoL) treatments. Transportation from the distribution center (e.g., supermarkets) to costumer’s household is not considered. Moreover, we assume that during the use phase, the analyzed dark chocolate does not need refrigeration, and, given its quality, it is consumed as it is (no melting or re-tempering).

Concerning system boundaries, two methodological hypotheses drawn from the General Program of the International EPD system are adopted (International EPD System, 2015a). Firstly, a “zero-burden” hypothesis is assumed for the in-flow materials produced through a recycling process (cardboard). This implies that the impacts related to the first life of those materials do not affect the secondary one. Secondly, no benefits are attributed to the system for the energy recovery obtained through the incineration of a fraction of the outflowing waste.

### 2.1.3. Data source and quality

In the present study, both primary and secondary data are used. Primary data were provided by the Italian chocolate company and collected during the period 2014-2015. They include information regarding the Peruvian cocoa beans provisioning (from mature plantations aged between 15 and 20 years) and the manufacturing within the company. Secondary data are used, instead, for *other* cocoa beans imported from different countries in Central and South America and Africa (i.e., Dominican Republic and Uganda), sugar, packaging, auxiliary materials, and End-of-life treatments (Wernet et al., 2016). Finally, transportation distances are primarily known except for (i) sugar cane and auxiliary materials (Ecoinvent 3.3 database), (ii) *other* cocoa beans (EcotransIT, http://www.ecotransit.org) and (iii) the inputs required for their cultivation (Ecoinvent 3.3 database). Main data and sources are summarized in Table 2.

**Table 2. Inventory data types and sources**

| **Life Cycle Phase** | Technological flow | Source | Unit Process | Data Type |
|---|---|---|---|---|
| **Cultivation** | Peruvian cocoa beans | Chocolate producers | UP1 | Primary |
| | *Other* cocoa beans | Ecoinvent 3.3 | UP2 | Secondary |
| **Raw materials production** | Sugar | Ecoinvent 3.3 | UP3 | Secondary |
| | Packaging | Ecoinvent 3.3 | UP4 | Secondary |
| | Auxiliary materials | Ecoinvent 3.3 | UP5 | Secondary |
| **Transportation to manufacturing** | Peruvian cocoa beans | Chocolate producers | UP1 – company | Primary |
| | *Other* cocoa beans | http://www.ecotransit.org/ | UP2 – company | Primary |
| | Sugar from sugar beet | Chocolate producers | UP3 - company | Primary |
| | Sugar from sugar cane | Ecoinvent 3.3 | UP3 – company | Secondary |
| | Packaging | Chocolate producers | UP4 – company | Primary |
| | Auxiliary materials | Ecoinvent 3.3 | UP5 – company | Secondary |
| **Chocolate Industry** | Chocolate production | Chocolate producers | UP8/UP9/UP10/UP11 | Primary |
| | Energy Production | Chocolate producers | UP7 | Primary |
| | Industrial Waste Treatment | Ecoinvent 3.3 | UP6 | Secondary |

| | | | | |
|---|---|---|---|---|
| **Downstream phase** | Transportation | Assumed (see Section 3.3) | UP12/UP13/UP14 | Secondary |
| | EoL treatment (packaging waste) | Ecoinvent 3.3 | UP13/UP14 | Secondary |

### 2.1.4. Allocation procedure

Allocation procedures are applied in two phases. The first one regards cocoa shells, which constitutes one of the outflows of both *RM* and *RMP* (Figure 3). Although shell mass is about 13-15% of cocoa beans, they are considered as surplus because their economic value is negligible if compared to the one of cocoa derivatives. With this assumption, 100% of impacts of *RM* unit are allocated to Peruvian cocoa liquor entering the conching phase and all the impacts of the *RMP* unit are allocated to the three cocoa derivatives (liquor, powder and butter) adopting a mass allocation criterion (see Table S.6 in the Supplementary materials). The second allocation procedure regards the disaggregation of heat, cooling energy, water, auxiliary materials, wastewater and industrial waste among the unit processes in the manufacturing plant, because only aggregated data for the whole production are available. Environmental impacts are allocated to each production unit (from UP8 to UP11) adopting an energetic criterion, based on primary data of electric energy consumptions specific for each unit (Table 2). The only exception is the detergent, which is totally allocated to the *TP* unit since it is used just to wash the molds.

## 2.2. Impact Assessment Method

The flows of materials and energy collected in the LCI are translated into environmental impacts through the use of the CML-IA 2001 assessment method (baseline for eutrophication, ozone layer depletion, photochemical oxidation, global warming and abiotic depletion categories; and non-baseline for acidification category) (Guinée, 2002). This choice has been made according to the General Programme Instructions of the international EPD System (International EPD System, 2015). In addition, the Cumulative Energy Demand (CED, version 1.09) is assessed (Frischknecht et al., 2007) to calculate the direct and indirect energy uses due to the chocolate under study

(Huijbregts et al., 2006). In our study, the calculation of CED includes non-renewable (from fossil fuels, nuclear) and renewable (from wind, solar, geothermal, and water) energy sources. In agreement with the scope of our study aimed at quantifying the energy used in the chocolate supply chain, the energy embedded in the biomass of trees (such as the energy derived from the sun and captured in the biomass through photosynthesis) is excluded from the energy balance. The calculation is performed with the software PRéConsultants SimaPro 8.3. Since a VOCs[1] characterization factor for photochemical oxidation is not provided by the method, the assumption is 0.337 kg $C_2H_4$/kg VOC following the Environdec guidelines (Heijuns, 1992).

### 2.3. Sensitivity analysis

After the LCIA, a sensitivity analysis is performed to support the interpretation of the LCA results. Firstly, the methodological assumption concerning the allocation of impacts to the cocoa shells is evaluated comparing different allocation scenarios. Secondly, we assessed and compared alternative scenarios of the life cycle phase emerged as environmental hotspots from the LCIA.

## 3. Life Cycle Inventory

The inflows and outflows of energy and materials involved in the studied system are presented in the next sections following the upstream-, core- and downstream partitioning.

### 3.1. Upstream Phase

Upstream processes include the production of all the material required to produce the dark chocolate bars. As previously described, the main ingredient is cocoa from high-quality Peruvian cocoa beans (UP1). 590 g of Peruvian cocoa beans per FU are produced in mature plantations with no use of chemicals, because soil fertility is guaranteed by the litter produced by cocoa and shading trees and by the cocoa pods, which are left on the ground (Jacobi et al., 2014). Once cocoa pods are manually harvested, beans are extracted and transported to a site where the fermentation and the

---

[1] VOCs (Volatile Organic Compounds) are linked to odor compound mostly emitted in the roasting phase.

sun-drying phases occur without any energetic inputs. The production of a blend of *other* cocoa beans (UP2, 530 g per FU) used for cocoa butter and powder is modelled through Ecoinvent 3.3[2]. Sugar is the second main ingredient (137 g/FU) and its production is modelled through Ecoinvent 3.3 database (Wernet et al., 2016). The sugar provisioning is based on the fluctuations of financial market, and, according to the company statistics, a 50:50 ratio between sugar beet and sugar cane is assumed. In addition to food flows, the upstream phase includes the production of packaging (UP4) and auxiliary materials (UP5). Specifically, the 18 g/FU aluminum foil is produced in Italy from primary aluminum and it is modelled using Ecoinvent 3.3 database (i.e., starting from ingots, 0.2 mm thick sheets are obtained). Concerning the cardboard (118 g/FU), the database process “folding boxboard/chipboard {GLO}” is considered because no primary information about the production is available (Wernet et al., 2016). Finally, three auxiliary materials are included in the study and modelled through the Ecoinvent 3.3: jute bags for cocoa beans (14.5 g/FU), soap used for washing chocolate molds (375 mg/FU) and lubricant oil for the equipment service (88 mg/FU).

## 3.2. Core Phase

The core phase is composed of two main steps: the transportation of input materials from their production sites to the chocolate factory and the chocolate manufacturing.

### 3.2.1 Transportation of inputs materials

Each input material required for the chocolate production is characterized by specific itineraries and transportation means. The itinerary of cocoa beans is composed of three segments: a first route from the cultivation site to a departure port, a trans-oceanic ship transport to an Italian port and the final transportation to the chocolate production plant (Table S.1 in the Supplementary materials). According to the company statistics, we assumed that 50% *other* cocoa beans (530 g for FU) is

---

[2] Since the company major cocoa beans suppliers (i.e. Dominican Republic and Uganda) are not present in Ecoinvent 3.3, we selected “Cocoa bean {RoW}| cocoa beans production, sun dried, Alloc Rec, U”. Given the mature age of the analyzed plantations (more than 25 years), field preparation, land-use change and carbon storage are not included in the present LCI.

imported from Dominican Republic, while the other 50% from Uganda. Additional primary data regard the distances travelled by sugar from sugar beet (800 km) and packaging components (aluminum travels for 30 km and the cardboard for 230 km), while transportation mean assumed is “freight, lorry 7.5-16 metric ton, EURO4” from Ecoinvent 3.3 (Wernet et al., 2016). Finally, information on the transportation of sugar from sugar cane and auxiliary materials is taken from Ecoinvent 3.3 database.

### 3.2.2 Chocolate manufacturing

Chocolate manufacturing is composed of four unit processes from UP8 to UP11 (Figure 3) and involves all the steps necessary to transform raw cocoa beans into chocolate. UP8 produces 501 g of Peruvian cocoa liquor entering the following phase together with 160 g of cocoa powder and 202 g of cocoa butter produced in UP9. The latter produces additional 98 g of cocoa liquor, which is not used for the product under study. In the conching unit, the output of *RM* and *RMP* are mixed with 137 g of sugar. The obtained paste is refined to reduce grain size below 20 microns and then is conched to remove compounds that can alter chocolate aroma. The output is 1 kg of a liquid paste ready to be tempered and packed. Focusing on energy flows, the trigeneration plant (UP7) supplies about 98% of total electricity needed in the process (0.91 kWh out of the 0.93 kWh required by the entire process per FU), as well as heat and cold energy flows (0.64 and 0.27 kWh/FU, respectively). Additional 0.057 $Sm^3$/FU of natural gas are needed, especially due to the roasting phase. The main inputs and outputs referred to the production of one FU are summarized in Table 3.

**Table 3. Main LCI data concerning dark chocolate manufacturing (referred to FU)**

| **INPUT** | | **unit** | **Unit Process** | | | | |
|---|---|---|---|---|---|---|---|
| | | | UP8 | UP9 | UP10 | UP11 | Total |
| Energy | electricity (trigeneration) | kWh | 0.25 | 0.18 | 0.29 | 0.19 | 0.91 |
| | heat (trigeneration) | kWh | 0.18 | 0.13 | 0.21 | 0.13 | 0.64 |
| | cooling (trigeneration) | kWh | 0.07 | 0.05 | 0.08 | 0.06 | 0.27 |
| | electricity (national grid) | kWh | 0.005 | 0.004 | 0.006 | 0.004 | 0.019 |
| | natural gas (national grid) | $Sm^3$ | 0.028 | 0.018 | 0.007 | 0.004 | 0.057 |
| Ingredients | Peruvian cocoa beans | g | 590 | - | - | - | 590 |
| | *other* cocoa beans | g | - | 530 | - | - | 530 |
| | Sugar | g | - | - | 137 | - | **137** |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| Others | aluminum foil | g | - | - | - | 18 | 18 |
| | Cardboard | g | - | - | - | 118 | 118 |
| | Detergent | mg | - | - | - | 374.7 | 374.7 |
| | lubricant oil | mg | 24.2 | 17.6 | 27.8 | 18.4 | 88 |
| | water (well and grid) | l | 0.7 | 0.9 | 1.0 | 0.7 | 3.3 |
| **OUTPUT** | | | UP8 | UP9 | UP10 | UP11 | Total |
| Cocoa derivatives | Peruvian cocoa liquor | g | 501 | - | - | - | **501** |
| | cocoa powder | g | - | 160 | - | - | **160** |
| | cocoa butter | g | - | 202 | - | - | **202** |
| | cocoa shells | g | 76 | 55 | - | - | 131 |
| | *other* cocoa liquor | g | - | 98 | - | - | 98 |
| | liquid dark chocolate | g | - | - | 1,000 | - | 1,000 |
| | **Tempered and packed dark chocolate** | g | - | - | - | 1,000 | **1,000** |

Chocolate manufacturing causes direct emissions into air and water, and produces solid waste. Specific data for each unit process can be derived from air emissions samples provided by the company (Table 4). RM, RMP and conching units emit particulates, while VOCs are attributed only to *RM* and *RMP* units. The trigeneration system releases carbon monoxide and $NO_x$, while carbon dioxide is emitted by all the manufacturing units and the trigeneration system (from UP7 to UP11). The company produces different types of industrial wastes (UP6). Packaging wastes (e.g., paper, plastic, wood, metals and iron) are sent to a recycling center and only transportation to a collection site is considered. For other waste, like sludge, food waste, waste mineral oil and used fluorescent lamps, transportation is modelled through primary data (transportation distances to incineration and landfill), while the final treatment is modelled through database.

**Table 4. Main emissions data, due to the FU manufacturing, used in the LCI (TSP is Total Suspended Solids)**

| **Emissions of chocolate manufacturing** | | | **Units** | UP8 | UP9 | UP10 | UP11 | **Total** |
|---|---|---|---|---|---|---|---|---|
| **from UP8 to UP11** | Emissions to air | $CO_2$ | g | 51.9 | 37.5 | 11.8 | 7.8 | **109.0** |
| | | VOCs | mg | 80.5 | 48.4 | - | **-** | **128.9** |
| | | $PM_{10}$ and $PM_{2.5}$ | mg | 13.6 | 8.1 | 0.9 | **-** | **22.6** |
| | | | **Units** | | | **Total** | | |
| | Emissions to water | TSP | g | | | **1.11** | | |
| | | BOD5 | g | | | **1.35** | | |
| | | COD | g | | | **3.25** | | |
| | | Oils | mg | | | **31.68** | | |
| | | $SO_4$ | mg | | | **53.97** | | |

| | | | | |
|---|---|---|---|---|
| | | Cl | mg | **32.85** |
| | | $F^-$ | mg | **9.15** |
| | | P tot | mg | **2.82** |
| | | $NH_4$ | mg | **30.27** |
| | | Surfactant | mg | **115.43** |
| | | N tot (TKN) | mg | **84.48** |
| | Waste | raw sewage sludge | g | **1.69** |
| | | municipal solid waste | g | **5.19** |
| | | plastic packaging | mg | **2.26** |
| | | metals packaging | mg | **0.11** |
| | | wood packaging | mg | **1.67** |
| | | cardboard packaging | mg | **3.30** |
| | | iron and steel | mg | **0.54** |
| | | waste mineral oil | mg | **0.09** |
| | | | **Units** | **Total** |
| **UP7** | Emissions to air | $CO_2$ | g | **435.0** |
| | | $NO_x$ | g | **1.0** |
| | | CO | g | **0.7** |

### 3.3. Downstream Phase

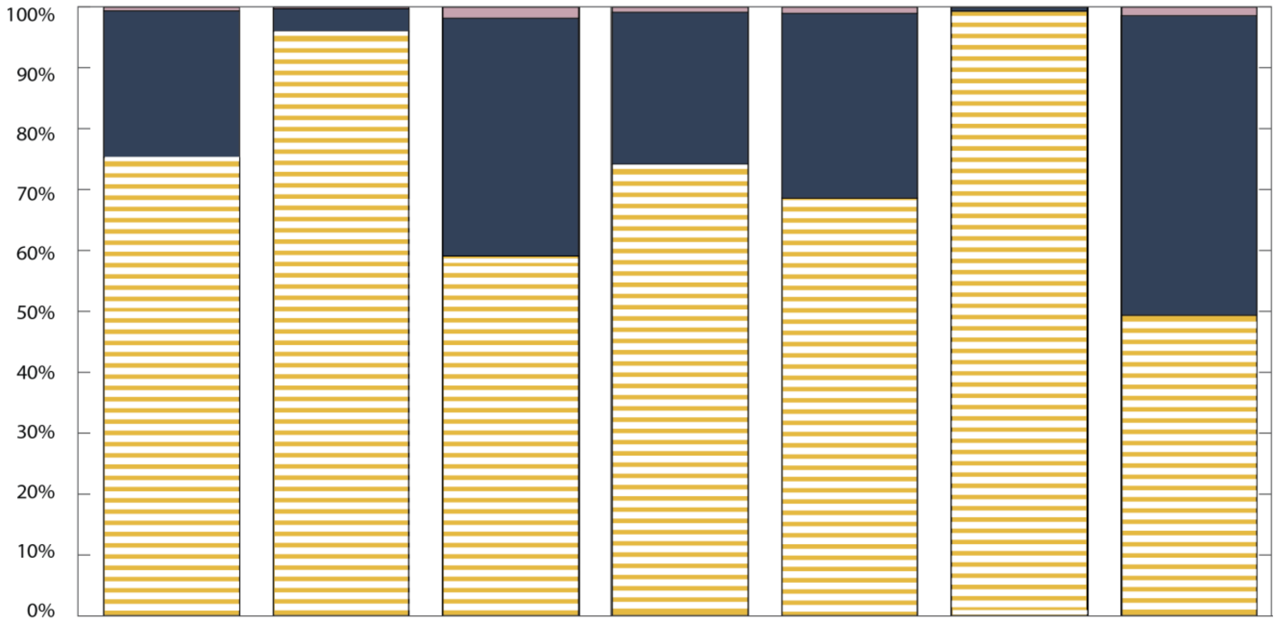
Once exited the production plant, the packed chocolate is distributed. A regional distribution within an average distance of 150 km and with a “EURO4, lorry 7.5-16 metric ton” is assumed. This is in line with the real market covered by the analyzed product. For both packaging components, EoL treatments are modelled according to the average Italian scenario (Table S.2, Supplementary materials) (CiAl, 2014; Comieco, 2015). For the recycled fraction, only transportation is considered, while for the fraction sent to disposal and incineration, both transportation and final treatment are taken into account (International EPD System, 2015b, 2014). We assumed a distance of 50 km (freight, lorry, 7,5-16 metric ton EURO4) for the collection of packaging waste (recycling, incineration and landfill) and other 50 km for transportation from the collection center to final treatment (incineration and landfill).

## 4. Life Cycle Impact Assessment

LCIA results are reported and analyzed starting from the overall process and, consequently, increasing the detail on the main unit processes.

## 4.1. Overall process

Figure 4 shows the impacts caused by the overall process disaggregated into upstream, core and downstream phases. Upstream processes have the highest contribution on abiotic depletion (1.1E-05 kg $Sb_{eq.}$, 99% of total impact), eutrophication (2.45E-02 kg $PO_4^{3-}{}_{eq.}$, 96% of total impact), acidification (1.7E-02 kg $SO_{2\ eq.}$, 75% of total impact) and photochemical oxidation categories (8.04E-04 kg $C_2H_{4eq.}$, 74% of total impact), mainly due to the cultivation of both *other* cocoa beans and sugar cane, and to packaging production. The core phase causes significant impacts on global warming (1.03E+00 kg $CO_{2eq.}$, 39% of total impact) and ozone layer depletion (1.73E-07 kg CFC-$11_{eq.}$, 30% of total impact). Both contributions are mainly due to the supply and use of natural gas in the chocolate manufacturing. The total value of CED is 33.75 MJ/FU (4% renewable and 96% non-renewable) and it is equally split between upstream and core processes (49% each). Finally, downstream processes always represent negligible contributions, which range from 0.2% on eutrophication to 1.8% on global warming category.



| | Acidification<br>kg $SO_2$ eq. | Eutrophication<br>kg $PO_4^{3-}$ eq. | Global Warming<br>kg $CO_2$ eq. | Photochemical oxidation<br>kg $C_2H_4$ eq. | Ozone layer depletion<br>kg CFC-11 eq. | Abiotic depletion<br>kg Sb eq. | CED<br>MJ |
|---|---|---|---|---|---|---|---|
| ▤ Upstream | 1.70E-02 | 2.45E-02 | 1.55E+00 | 8.04E-04 | 3.91E-07 | 1.10E-05 | 1.67E+01 |
| ■ Core | 5.44E-03 | 9.46E-04 | 1.03E+00 | 2.71E-04 | 1.73E-07 | 6.94E-08 | 1.66E+01 |
| □ Downstream | 1.29E-04 | 5.92E-05 | 4.64E-02 | 8.66E-06 | 5.54E-09 | 5.05E-10 | 4.60E-01 |

**Figure 4. Environmental impacts of the dark chocolate life cycle assessed through CML-IA 2001 and CED split into upstream, core and downstream processes**

Given the obtained results, we deepened the analysis of the main unit processes included in the upstream and in the core phase (Table S.5 in the Supplementary material).

## 4.2. Upstream Process

The upstream processes involve the production of all the input materials required to manufacture the dark chocolate bars. The cultivation of *other* cocoa beans, imported from Dominican Republic and Uganda, causes the highest fractions on five of the seven impact categories considered. The production of inorganic fertilizers and pesticides generates 98% of total impact on AD, 63% on ODP, 25% on POC and 30% on CED (1.08E-05 kg $Sb_{eq.}$, 3.60E-07 kg CFC-$11_{eq.}$, 1.36E-04 kg $C_2H_{4eq.}$ per FU, and 9.98 MJ, respectively). The application of fertilizers and the related direct field emissions (i.e., nitrate, ammonia and nitrous oxide) mostly influence the EU, AC and GW categories (92%, 62%, and 42% of total impacts, respectively). The production of sugar causes the highest contributions to the photochemical oxidation category (35%) due to the carbon monoxide emissions from pre-harvest burning of sugar cane field. Finally, packaging has considerable fractions of impacts on global warming (13%, 0.37 kg $CO_{2eq.}$/FU), photochemical oxidation (13%, 0.14 $C_2H_{4eq.}$/FU) and acidification (10%, 2.3 g $SO_{2eq.}$/FU) due to heat and electricity required by packaging production process.

### 4.3. Core Process

Core processes include the transportation of the inputs to the production plant and chocolate manufacturing. A first remarkable cause of environmental impacts is the transportation of cocoa beans along global distances. The outcomes shown in Figure 5 highlight that the trans-oceanic ship transportation is responsible for about 14% of total acidification, mainly due to the sulfur dioxide emitted by ships. Cocoa beans transportation also generates 0.22 kg $CO_{2eq.}$/FU (9% of total GW) and 3.44 MJ (10% of total CED). Chocolate production is an energy consumptive process (Perez Neira, 2016; Vesce et al., 2016) and its contribution to total CED is 39% (13 MJ/FU), mostly from non-renewable sources (Figure S.2 in the Supplementary Materials). It generates 28% of total global warming: 0.58 kg $CO_{2eq.}$/FU (78% of the whole manufacturing, i.e. UP6-UP11) are associated with the trigeneration plant (UP7), while 0.16 kg $CO_{2eq.}$/FU are due to the rest of chocolate production (UP6, UP8, UP9, UP10, UP11). Moreover, the supply of natural gas consumed in the process causes a significant impact on ozone depletion: halon leakages from the methane transportation pipelines system generate, indeed, about 23% of impact on the category.

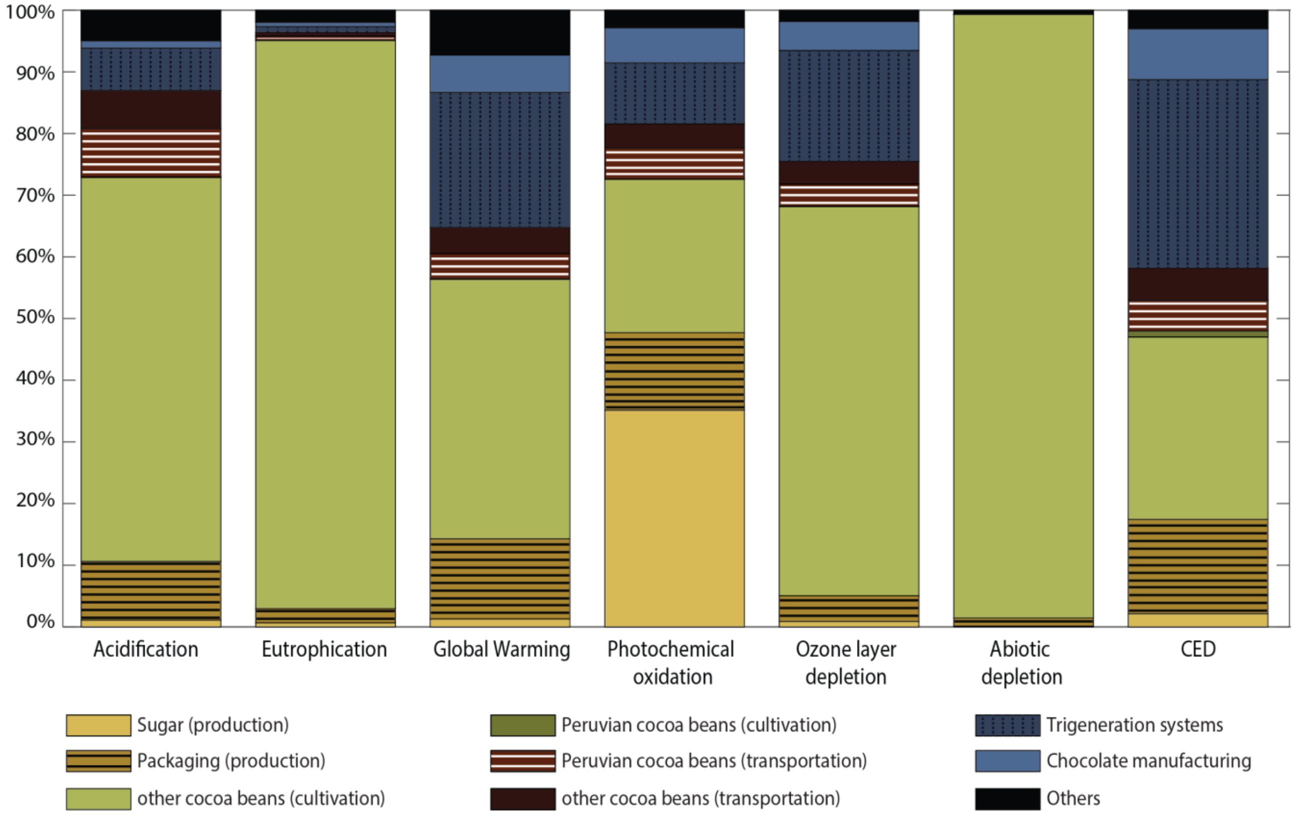


**Figure 5. Total impacts disaggregated into different unit processes. '*Others*' includes the production and transportation of jute and packaging, sugar transportation, and processes integrated in the downstream phase (i.e., distribution and EoL treatments). The impacts of this aggregated category ('*Others'*) range from 1% to 7% on the AD and on the GW categories.**

## 5. LCA interpretation and sensitivity analysis

To support the results interpretation, we analyze the methodological assumption on cocoa shells allocation and we deepen the analysis of environmental hotspots emerged along the chocolate supply chain thanks to the LCA: the provisioning of cocoa beans (both the cultivation and the transportation to the production plant) and the energy supply at the manufacturing phase.

### 5.1. Cocoa Shells Allocation

In this study cocoa shells are considered as a "surplus" flow with a null allocation of environmental impacts (base scenario, BS). Nevertheless, cocoa shells can be sold to other companies for a further recovering of cocoa butter or for other purposes (Abiola and Tewe, 1991; International Cocoa Organization, 2003; Kouamé et al., 2011), eventually becoming a co-product, with a consequent application of allocation procedures in LCA. We thus compare the BS with an economic- and a mass-based allocation. Mass allocation factors ($\gamma_i$) are obtained from in-flows and out-flows of *RM* and *RMP* unit process, while the economic factors ($\lambda_i$) are based on economic values ($\delta_i$) of cocoa shells, cocoa powder, cocoa liquor and cocoa butter, which were provided as primary data by the company (Table S.6, Supplementary materials).

$$\gamma_i = \frac{m_i}{\sum_i m_i} \qquad \lambda_i = \frac{\delta_i m_i}{\sum_i \delta_i m_i} \tag{1}$$

From the obtained results (Figure S.3, Supplementary materials), it emerges that the *economic scenario* presents only a negligible reduction in chocolate impacts with respect to the *base scenario*, due to the small economic value of cocoa shells. On the other hand, the *mass scenario* entails a reduction of impacts ranging from 6.5% (on the global warming) to 12% (on the abiotic depletion).

### 5.2. Cocoa beans provisioning

The results obtained from LCI and LCIA highlighted the relevant contribution of cocoa beans provisioning to environmental impacts, as well as the high variability of environmental performances depending on the origins and type of cultivation (i.e., Peruvian vs. *other* cocoa beans). The cultivation of cocoa is located in tropical environments, from South America to tropical Africa and South-East Asia. Cocoa plantations range from the monoculture to the more complex agroforestry (Wood and Lass, 2008; Utomo et al., 2015) and are managed with extremely different practices (e.g., irrigated or rain-fed, different fertilizer types or dosages). Therefore, the magnitude of impacts on the environment and on the ecosystem services varies across plantations (Bartzas et al., 2017). As previously explained, the Italian company has provided primary data about the provisioning of the high-quality Peruvian cocoa beans (from mature cocoa plantation), while *other* cocoa beans have been modeled through Ecoinvent 3.3 database, assuming generic cocoa beans. Given the wide variety of cocoa origins and cultivations, this assumption needs a deeper investigation. We dedicated the sensitivity analysis to the 530 g of *other* cocoa beans, while the production of 590 g of Peruvian cocoa beans remains constant, because they are the peculiar feature of the dark chocolate under study and cannot be modified. We compare alternative cocoa beans provisioning scenarios defined through the Ecoinvent 3.3 database, which provides data about four types of cocoa beans from different areas of the world (Ivory Coast ‘CI’, Ghana ‘GH’, Indonesia ‘ID’, and Rest-of-the-World which is Base Scenario in this study ‘BS’), managed with different practices (e.g., ID is rain-fed and intensively fertilized, while GH is irrigated and lower fertilized). Besides cocoa cultivation, the travelling distance from the cultivation site to the chocolate manufacturing plant increases from 6,982 km in the case of Ghanaian and Ivorian cocoa to more than 11,500 km in the cases of Peruvian (11,823 km) and Indonesian (12,032 km) ones. The four scenarios (BS, CI, GH and ID) are compared through the CML-IA 2001 impact assessment method and CED indicator.

The results, reported in Figure 6 (axis labels), show that a different choice in the cocoa provisioning can significantly reduce the environmental impacts of the whole chocolate life cycle from -5% (ODP) to -69% (EU). The production of cocoa beans in Indonesia (ID) generates the highest impacts on the majority of the categories, mainly due to the direct field emissions caused by the large use of fertilizers. For instance, nitrous oxide emissions cause 55% on the total GW, ammonia 71% on the AC and nitrate 81.2% on the EU categories (see Table S.7 in the Supplementary Materials). The same field emissions also represent significant fractions in the CI scenario: 48.1% of AC, 73% of EU and 36.5% of GW. Different outcomes are obtained for Ghanaian cultivation, in which the most relevant contributions to GW, AC and CED (51%, 30% and 62%, respectively) are due to the facilities used for the irrigation of plantation. Specifically, the value of CED (35 MJ/FU) is 1.1 MJ/FU higher than ID and 4 MJ/FU than CI.

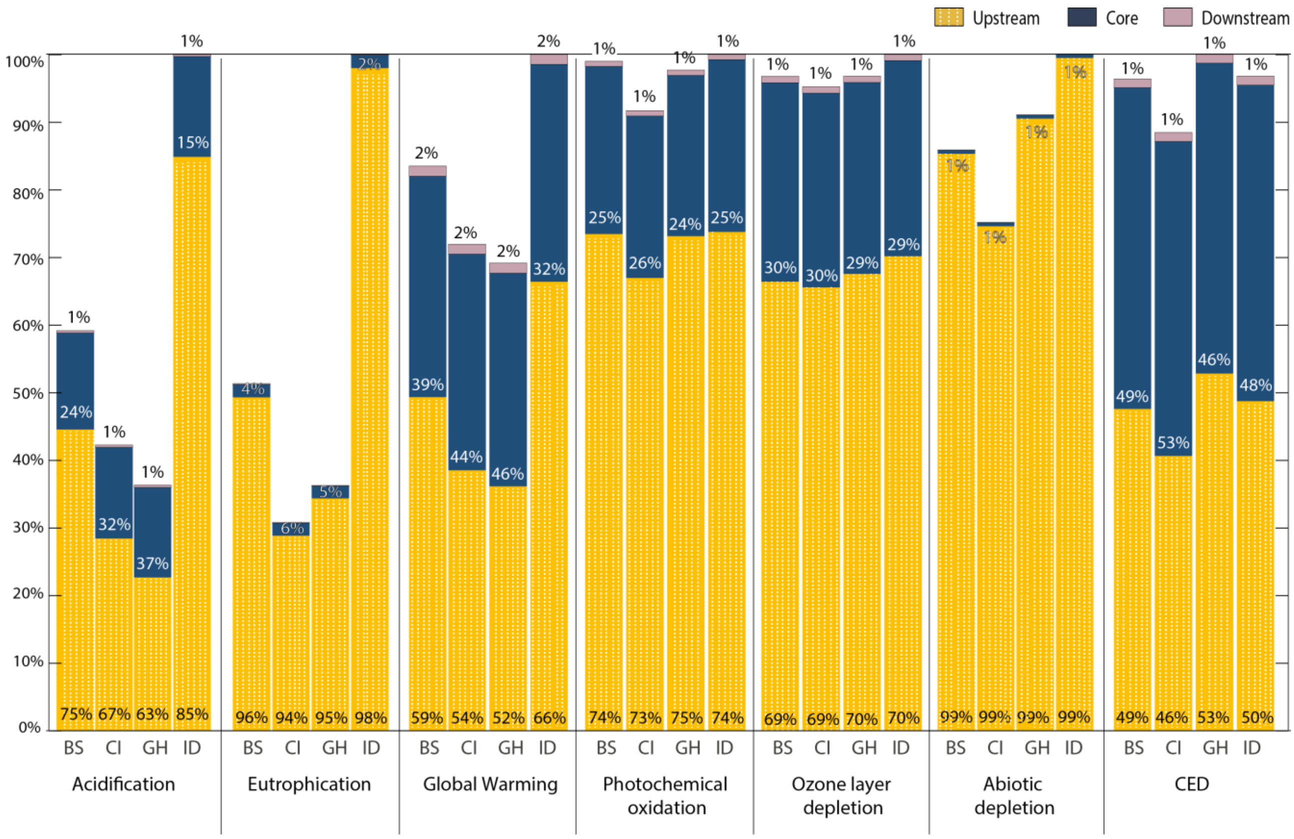


**Figure 6. Comparison of the environmental impacts of the whole life cycle of 1 kg of dark chocolate assuming four different cocoa provisioning scenarios (100% is the worst scenarios, the one with the highest impacts) according to the split into upstream, core and downstream processes. Axis labels refer only to the total impact value of the scenarios with respect to the worst, while the breakdown of each scenario is represented with the labels in the histogram columns. [BS: Base Scenario; CI: Ivory Coast; GH: Ghana; ID: Indonesia]**

Besides the variations in total values, also the breakdown of impacts between upstream, core and downstream differs in the four scenarios (Figure 6, labels in the columns). For instance, the upstream contribution to the total value of global warming increases from 52% in the GH scenario to 66% in the ID scenario, while the contribution to the total value of acidification ranges from 63% for GH to 85% in the ID case. Since the selected categories do not assess the environmental impacts caused by the application of pesticides, a preliminary assessment on human toxicity and eco-toxicity categories (fresh water eco-toxicity, marine eco-toxicity and terrestrial eco-toxicity) is carried out through the CML-IA 2001 method. The results described in section S.2.2.3 (Supplementary materials) show that cocoa beans from Indonesia have the highest impacts on three of the four toxicity categories, i.e., human, freshwater and terrestrial eco-toxicity, while GH scenario causes the highest impact on marine eco-toxicity.

This preliminary sensitivity analysis highlights the importance of the agricultural and transportation phases of cocoa beans in the assessment of chocolate life cycle, confirming recently published outcomes about permanent cultures (Bartzas et al., 2017) and variability of agroecosystems (Notarnicola et al., 2017).

### 5.3. Energy

The LCA results show that the energy-intensive chocolate manufacturing causes a relevant fraction of the global warming impact category (about 22% of the total). The Italian chocolate company is equipped with a recently renovated and efficient production plant based on a trigeneration system including the best technologies available on the market. In order to investigate possible environmental benefits guaranteed by this efficient energy supply system, we compared it with the Italian scenario, i.e., the required electricity, thermal and cooling energy are supplied by the Italian national grid (Ecoinvent 3.3 database). Results reported in Figure 7 show that the trigeneration system enables to reduce impacts from -25% to -91%, on the global warming and on the abiotic depletion categories, respectively. This improvement is mainly due to the usage of natural gas instead of the hard coal and oil, which characterizes the Italian energetic mix. The only exception regards the ozone layer depletion category, where an increase of about 8% is due to the leaks of halon gas along the supply chain of natural gas.

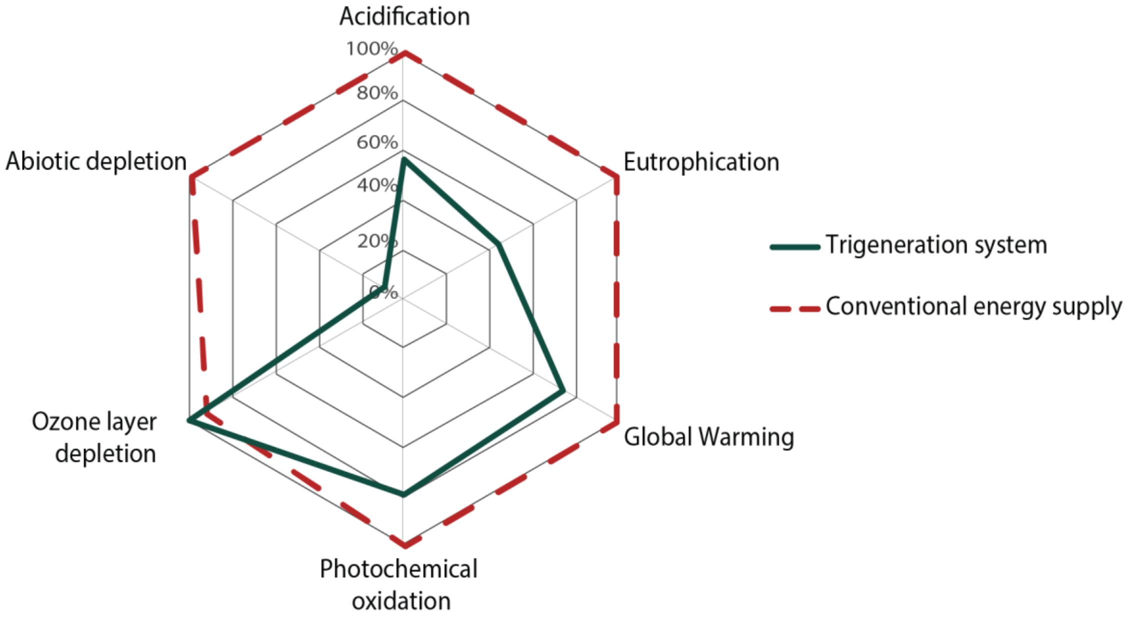


**Figure 7. Comparison of environmental impacts due to two different energy supply scenarios, i.e., trigeneration and conventional energy supply**

The results of CED are separately reported to highlight the contributions of non-renewable and renewable energy. Figure 8 shows that the total cumulative energy demand increases from 33.75 MJ/FU of base scenario to 36.75 MJ/FU (+9 %) with conventional energy supply. Focusing on the renewable resources, the conventional energy supply is characterized by a fraction of 6.2% guaranteed by the Italian national mix, while in the base scenario it is reduced to 4% due to the use of natural gas.

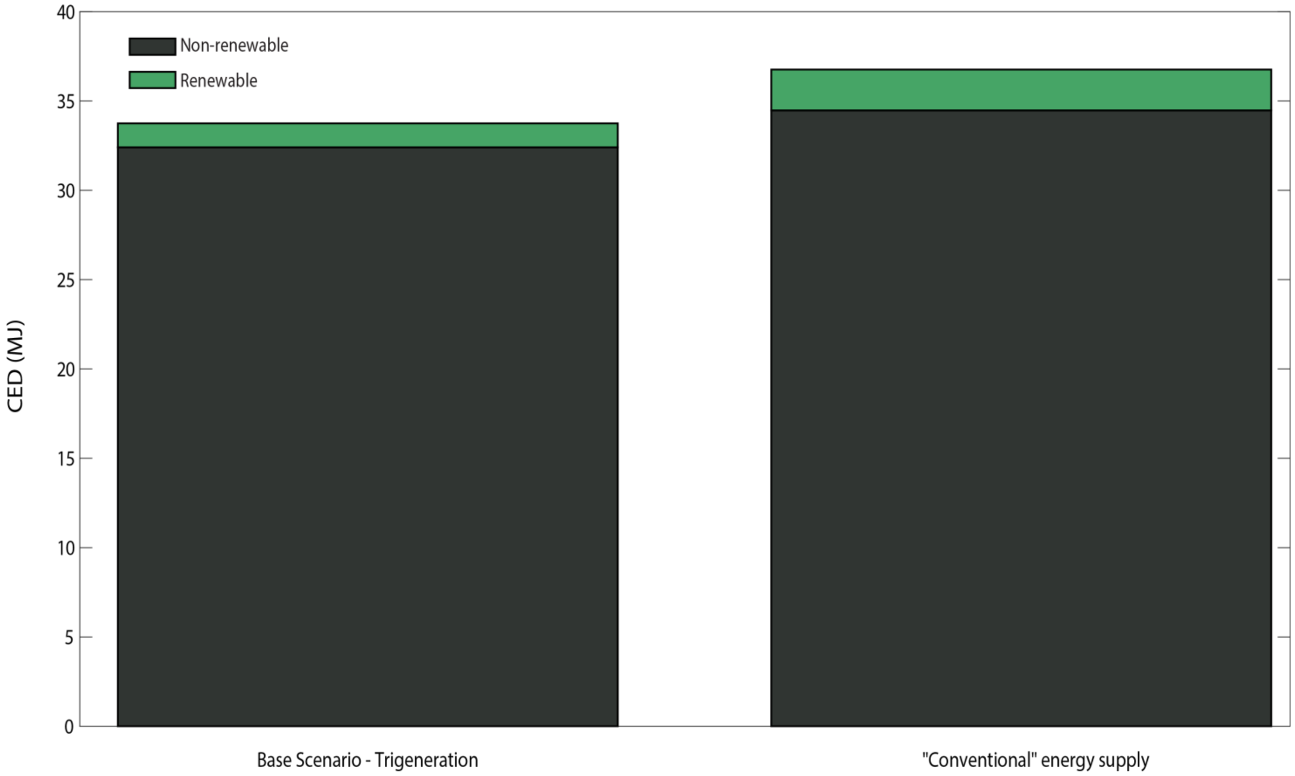


**Figure 8. Sensitivity analysis on energy provisioning in terms of CED (MJ): comparison between an energy supply system based on a trigeneration system and a system based on the average Italian market**

## 6. Discussion and conclusions

Despite the increasing interest in environmental sustainability of the agri-food sector, environmental assessments and certifications of chocolate and other cocoa derivatives are still missing (Figure 2). Given this lack and the increasing global demand for cocoa-derivative products, complete environmental assessments are fundamental to support chocolate producers in improving the environmental sustainability of their production. To this aim, we perform a *cradle-to-grave* LCA of an Italian dark chocolate mainly based on primary data. Our primary objectives are (i) the identification of the environmental hotspots along the chocolate supply chain and (ii) the assessment of possible alternative scenarios. The outcomes obtained through the CML-IA 2001 method are in line with the studies available in the literature. For instance, the resulting global warming of 2.62 kg $CO_{2eq.}$ per FU is comparable to the values reported in Büsser and Jungbluth (2009) (2.1 kg $CO_{2eq.}$) and Perez Neira (2016) (2.57 kg $CO_{2eq.}$). Referring to the different phases of the chocolate life cycle, upstream and core processes cause the highest fractions of the considered impact categories. Specifically, the production of raw materials has the highest impacts on abiotic depletion, eutrophication and photochemical oxidation, while cocoa beans transportation and packaging production considerably contribute to global warming, CED and photochemical oxidation. The obtained result on global warming category due to cocoa transportation (0.22 kg $CO_{2eq.}$ per kg of beans) is within the same order of magnitude of those obtained in Perez Neira et al. (2014) and Perez Neira (2016) (from 0.22 to 0.39 kg $CO_{2eq.}$). In addition, packaging production (0.34 kg $CO_{2eq.}$/FU) falls within the range between 0.28 and 1.91 kg $CO_{2eq.}$ per FU reported by Allione and Petruccelli (2012) and Perez Neira (2016). Finally, although the chocolate manufacturing is an optimized and efficient industrial process, it generates relevant impacts on global warming, ozone layer depletion, and CED due to energy requirements. Considering the overall core phase (transportation and manufacturing) together with the packaging production, our results (1.37 kg $CO_{2eq.}$ and 1.97E-07 kg CFC-$11_{eq.}$) are again in line to the ones found in existing literature: Vesce et al. (2016) reports 1.91 kg $CO_{2eq.}$ for global warming and 2.34E-07 kg CFC-$11_{eq.}$ for ozone layer depletion[3].

From the LCIA results, cocoa bean provisioning (i.e., cultivation and transportation) and energy supply at the manufacturing plant have emerged as environmental hotspots along the chocolate supply chain. Therefore, their investigation is deepened through a sensitivity analysis. The comparison of different scenarios of cocoa cultivation and origin confirms (i) the relevance of the environmental impacts caused by the agricultural phase (Roy et al., 2009) with respect to the whole life cycle, and (ii) the influence of agricultural ecosystems and practice variability on the environmental impacts (Notarnicola et al., 2017). Secondly, the in-depth analysis of energy supply for cocoa beans transformation allows to quantitatively assess the environmental benefits guaranteed by an efficient energy supply system, like the trigeneration plant, in comparison with a conventional energy supply.

---

[3] It is important to point out that in the present study the roasting phase of raw cocoa beans is included in the manufacturing process, whereas it is outside system boundaries in Vesce et al. (2016).

The proposed methodology and system modelling, together with the obtained outcomes (both LCI and LCIA and in-depth analysis) could support chocolate companies in assessing the environmental profile of their products and in taking strategic decisions to improve their environmental sustainability, like changing raw materials and/or the type of energy supply. For instance, if a company would decide to satisfy its cocoa demand only with Peruvian cocoa beans, it would consistently reduce its environmental impacts (i.e., from -42% for the POC up to -99% for AD and EU) with respect to a provisioning based on the Indonesian cocoa (Figure S.4, Supplementary materials). Further developments are required to improve the investigation of the agricultural phase (i.e. the collection of primary data and estimation of direct field emissions), to enlarge the evaluation to other environmental impact categories (e.g., water consumption, carbon balance between land-use change and relative $CO_2$ emissions and plantation storage, energy embedded in plantation) and to create a comprehensive methodological framework for the comparison of chocolate with other food and beverages (e.g., festive bread, beer, wine) under a nutritional, sensorial, cultural and social perspective (Rousseau, 2015; Notarnicola et al., 2016, 2017).

## Acknowledgments

The authors thank the ICAM S.p.A staff, and especially Eng. Antonello Ercole, for the constant support to this research, from the data collection to results discussion.

## Bibliography

Abiola, S.S., Tewe, O.O., 1991. Chemical evaluation of cocoa by-products. Trop. Agric. 68, 335–336.

Allione, C., Petruccelli, L., 2012. A Multicriteria Method for Assessing the Eco- performances of Food Packing. 2nd World Sustainability Forum. Avaiable on Webside: www.wsforum.org (accessed 30.08.17.).

Barona, E., Ramankutty, N., Hyman, G., Coomes, O.T., 2010. The role of pasture and soybean in deforestation of the Brazilian Amazon. Environ. Res. Lett. 5, 024002. doi:10.1088/1748-9326/5/2/024002

Bartzas, G., Komnitsas, K., 2017. Life cycle analysis of pistachio production in Greece. Sci. Total Environ. 595, 13–24. doi:10.1016/j.scitotenv.2017.03.251

Bessou, C., Basset-Mens, C., Tran, T., Benoist, A., 2013. LCA applied to perennial cropping systems: a review focused on the farm stage. Int. J. Life Cycle Assess. 18, 340–361.

doi:10.1007/s11367-012-0502-z

Bonamente, E., Scrucca, F., Rinaldi, S., Merico, M.C., Asdrubali, F., Lamastra, L., 2016. Environmental impact of an Italian wine bottle: Carbon and water footprint assessment. Sci. Total Environ. 560-561, 274–283. doi:10.1016/j.scitotenv.2016.04.026

Buratti, C., Fantozzi, F., Barbanera, M., Lascaro, E., Chiorri, M., Cecchini, L., 2017. Carbon footprint of conventional and organic beef production systems: An Italian case study. Sci. Total Environ. 576, 129–137. doi:10.1016/j.scitotenv.2016.10.075

Büsser, S., Jungbluth, N., 2009. LCA of Chocolate Packed in Aluminium Foil Based Packaging. ESU-services.

CiAl (Consorzio imballaggi Alluminio), 2014. Annual Report.

Comieco (Consorzio Nazionale Recupero e Riciclo degli imballaggi a base Cellulosica), 2015. 20° Rapporto.

EcoTransIT, 2014. EcoTransIT World - a sustainable move. URL: http://www.ecotransit.org/index.it.html (accessed 1.13.17).

FAO, 2011. The State of the World’s Land and Water Resources for Food and Agriculture. Managing Systems at Risk. Lancet 2, 285. doi:10.4324/9780203142837

FAO, 2016. AQUASTAT website. URL: http://www.fao.org/nr/water/aquastat/water_use/index.stm

FAO, 2017. FAOSTAT. URL: www.fao.org/faostat (accessed 6.05.17).

Frischknecht, R.; Jungbluth, N.; Althaus, H.J.; Doka, G.; Dones, R.; Hischier, R.; Hellweg, S.; Humbert, S.; Margni, M.; Nemecek, T.; Spielmann, M. 2007. Implementation of Life Cycle Impact Assessment Methods: Data v3.3. ecoinvent report No. 3, Swiss centre for Life Cycle Inventories, Dübendorf, Switzerland

Guinée, J.B., 2002. Handbook on life cycle assessment: operational guide to the ISO standards / Jeroen B. Guinée (final editor), Eco-efficiency in industry and science. Ecomed. doi:10.1007/BF02978897

Heijungs, R., 1992. Nordic Guidelines on Life-Cycle Assessment.

Huijbregts, M.A.J., Rombouts, L.J.A., Hellweg, S., Frischknecht, R., Hendriks, J.A., Van de Meent, D., Ragas, A. m J., Reijnders, L., Struijs, J., 2006. Is Cumulative Fossil Energy Demand a Useful Indicator for the Environmental Performance of Products? Environ. Sci. Technol. 40, 641–648. doi:10.1021/es051689g

International Cocoa Organization, 2003. Products that can be made from cocoa. Int. Cocoa Organ. URL https://www.icco.org/faq/52-by-products/115-products-that-can-be-made-from-cocoa.html (accessed 12.17.16).

International EPD System, 2014. Product Category Rules -Refined Sugar From Sugar Beet 1–16.

International EPD System, 2015a. General Programme Instruction for the International EPD® System (version 2.5).

International EPD System, 2015b. Product category Rules - Bakery Products 1–32.

International EPD System, 2016. URL: https://www.environdec.com.

IPCC, 2006. IPCC Guidelines for National Greenhouse Gas Inventories. Volume 4: Agriculture, forestry and other land use.

ISO, 2006a. ISO 14040:2006 Environmental Management - Life Cycle Assessment - Principles and Framework.

ISO, 2006b. ISO 14044:2006 Environmental Management - Life Cycle Assessment - Principles and Framework.

ISO, 2006c. ISO 14025:2006 Environmental labels and declarations - Type III environmental claims.

Jacobi, J., Andres, C., Schneider, M., Pillco, M., Calizaya, P., Rist, S., 2014. Carbon stocks, tree diversity, and the role of organic certification in different cocoa production systems in Alto Beni, Bolivia. Agrofor. Syst. 88, 1117–1132. doi:10.1007/s10457-013-9643-8

Kastner, T., Rivas, M.J.I., Koch, W., Nonhebel, S., 2012. Global changes in diets and the consequences for land requirements for food. Proc. Natl. Acad. Sci. U. S. A. 109, 6868–72. doi:10.1073/pnas.1117054109

Kouamé, B., Marcel, G., André, K.B., Théodore, D., Bouafou, A., Guy, K., Agr, I.J., Agri, R., 2011. Waste and by-products of cocoa in breeding : Research synthesis. Int. J. Agron. Agric. Res. 1, 9–19.

Moss, B., 2008. Water pollution by agriculture. Philos. Trans. R. Soc. Lond. B. Biol. Sci. 363, 659–66. doi:10.1098/rstb.2007.2176

Neira, D. P., Fernández, X. S., Rodríguez, D. C., Montiel, M. S., & Cabeza, M. D. (2016). Analysis of the transport of imported food in Spain and its contribution to global warming. Renewable Agriculture and Food Systems, 31(1), 37-48.

Notarnicola, B., Tassielli, G., Renzulli, P.A., Castellani, V., Sala, S., 2016. Environmental impact of food consumption in Europe. J. Clean. Prod. 140 (part-2), 753e765. http://dx.doi.org/10.1016/j.jclepro.2016.06.080.

Notarnicola, B., Sala, S., Anton, A., McLaren, S.J., Saouter, E., Sonesson, U., 2017. The role of life cycle assessment in supporting sustainable agri-food systems: A review of the challenges. J. Clean. Prod. 140, 399–409. doi:10.1016/j.jclepro.2016.06.071

Ntiamoah, A., Afrane, G., 2008. Environmental impacts of cocoa production and processing in Ghana: life cycle assessment approach. J. Clean. Prod. 16, 1735–1740. doi:10.1016/j.jclepro.2007.11.004

Perez Neira, D., 2016. Energy sustainability of Ecuadorian cacao export and its contribution to climate change. A case study through product life cycle assessment. J. Clean. Prod. 112, 2560–2568. doi:10.1016/j.jclepro.2015.11.003

Rajab, Y.A., Leuschner, C., Barus, H., Tjoa, A., Hertel, D., 2016. Cacao cultivation under diverse shade tree cover allows high carbon storage and sequestration without yield losses. PLoS One 11, e0149949. doi:10.1371/journal.pone.0149949

Recanati, F., Allievi, F., Scaccabarozzi, G., Espinosa, T., Dotelli, G., Saini, M., 2015. Global Meat Consumption Trends and Local Deforestation in Madre de Dios: Assessing Land Use Changes and other Environmental Impacts. Procedia Eng. 118, 630–638. doi:10.1016/j.proeng.2015.08.496

Rousseau, S., 2015. The role of organic and fair trade labels when choosing chocolate. Food Qual. Prefer. 44, 92–100. doi:10.1016/j.foodqual.2015.04.002

Roy, P., Nei, D., Orikasa, T., Xu, Q., Okadome, H., Nakamura, N., Shiina, T., 2009. A review of life cycle assessment (LCA) on some food products. J. Food Eng. 90, 1–10. doi:10.1016/j.jfoodeng.2008.06.016

Silva, A.R. de A., Bioto, A.S., Efraim, P., Queiroz, G. de C., 2017. Impact of sustainability labeling in the perception of sensory quality and purchase intention of chocolate consumers. J. Clean. Prod. 141, 11–21. doi:10.1016/j.jclepro.2016.09.024

Smith, P., Bustamante, M., Ahammad, H., Clark, H., Dong, H., Elsiddig, E.A., Haberl, H., Harper, R., House, J., Jafari, M., Masera, O., Mbow, C., Ravindranath, H.N., Rice, C.W., Abad Robledo, C., Romanovskaya, A., Sperling, F., Tubiello, F., 2014. Agriculture, Forestry and Other Land Use (AFOLU)., in: Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge.

Solazzo, R., Donati, M., Tomasi, L., Arfini, F., 2016. How effective is greening policy in reducing GHG emissions from agriculture? Evidence from Italy. Sci. Total Environ. 573, 1115–1124. doi:10.1016/j.scitotenv.2016.08.066

Statista, The statistics portal. Retail consumption of chocolate confectionery worldwide from 2012/13 to 2018/19. https://www.statista.com/statistics/238849/global-chocolate-consumption/ (accessed 16.06.17).

Tilman, D., Clark, M., 2014. Global diets link environmental sustainability and human health. Nature 515, 518–522. doi:10.1038/nature13959

Utomo, B., Prawoto, A.A., Bonnet, S., Bangviwat, A., Gheewala, S.H., 2015. Environmental performance of cocoa production from monoculture and agroforestry systems in Indonesia. J. Clean. Prod. 1–9. doi:10.1016/j.jclepro.2015.08.102

Vesce, E., Olivieri, G., Pairotti, M.B., Romani, A., Beltramo, R., 2016. Life cycle assessment as a tool to integrate environmental indicators in food products : a chocolate LCA case study. Int. J. Environ. Heal. 8, 21–37. doi:10.1504/IJENVH.2016.077660

Wernet, G., Bauer, C., Steubing, B., Reinhard, J., Moreno-Ruiz, E., Weidema, B., 2016. The ecoinvent database version 3 (part I): overview and methodology. Int. J. Life Cycle Assess. 21, 1218–1230. doi:10.1007/s11367-016-1087-8

Wood, G. A. R., & Lass, R. A. (2008). *Cocoa*. John Wiley & Sons.