NOTE:

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DISCLAIMER

This summary covers the results of an international survey of LCA (life-cycle analysis) studies. Two points should be noted:

- The results of the various studies are the responsibility of the authors.
- All existing data on the environmental performance of the various plant resource supply chains may not be presented in the LCA studies available to date.

Environmental Impacts of Plants Used for Chemical, Material and Energy Purposes

Status of Current Knowledge: Life-cycle Analysis (LCA)

Public Summary

October 2004

Public Summary

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1 *Introduction*

The use of agricultural and forest resources in bioproduct synthesis (chemistry, energy, materials) may offer important environmental advantages. Indeed, unlike the case of their fossil-based counterparts, the materials and renewable energies produced from biomass (agriculture, forest silviculture) can make it possible to reduce energy consumption and greenhouse gas emissions, and lessen impacts on air, water and soil. Their use would preserve fossil resources and promote the adoption of sustainable agricultural practices. However, environmental impacts can vary widely from one supply chain to another. Thus, reliable environmental assessments must be conducted before moving from presumption to certainty.

Because ADEME [the French Agency for Environment and Energy Management] is responsible for three programs relating to the development of plants for chemical and energy uses (AGRICE (Agriculture for Chemistry and Energy), the Wood Energy Program and the Wood Materials Program), it decided to review the state of current environmental knowledge of plant resource supply chains at the international level.

Carried out in collaboration with BG Ingénieurs-conseils and the Ecole Polytechnique Fédérale de Lausanne (EPFL), this project focussed on currently available life-cycle analysis (LCA) studies. LCA can be used to assess the potential environmental impacts of a system comprising all the activities (material and energy flows) associated with a product or service, from extraction of the raw materials, to disposal of waste. For a comprehensive, multi-criteria evaluation of environmental impacts, followed by production and interpretation of a quantified assessment, the LCA is the most well-developed tool available today.

The review, analysis, criticism and compilation of this assessment focussed on 10 non-food plant supply chains, divided into two groups based on the number of LCA studies published (Table 1).

Table 1 Distribution of LCA studies by plant resource supply chain

GROUP 1 MORE COMMONLY STUDIED AREAS	GROUP 2 RARELY STUDIED AREAS
Agrimaterials Ether alcohols (biofuels) Ester oils (biofuels) Forest biomass [bioenergy; heat & electricity]	Agricultural biomass [bioenergy; heat & electricity] Biopolymers Surfactants Hydraulic fluids and lubricants Solvents Chemical and other intermediates

2 *Objectives and Areas of Investigation*

The objective of the study is to equip ADEME with a decision-making tool that will improve the evaluation of the environmental gains generated by the various plant resource supply chains in question.

The authors of the study focussed on the following questions and issues:

- ♦ How much consistency exists among the results of the various LCAs conducted on the different plant resource supply chains?
- ♦ Is it possible to measure the energy gains and the potential reductions in greenhouse gas emissions when bioproducts are substituted for conventional ones?
- ♦ From an environmental point of view, what are the key parameters for promoting effective use of biomass?
- ♦ On what basis can the environmental impact and the energy gains observed in each plant supply chain be compared?
- ♦ What plant supply chains are the most promising from an environmental standpoint?

The purpose of the first part of the study is to determine the state of current LCA knowledge of plant resource supply chains. Rather than presenting data on each supply chain, a comprehensive, quantitative, qualitative and critical inventory of all available data is produced.

The second part of the study concentrates on a comparison among the various supply chains, demonstrating the advantages of plant supply chains over their fossil counterparts in the areas of non-renewable energy consumption and greenhouse gas emissions.

The third and final part of the study contains recommendations for the development of plant resource supply chains and suggests avenues for improving LCA knowledge.

3 *State of Current LCA Knowledge of Plant Resource Supply Chains*

3.1 *Quantity of available LCA knowledge*

The number of LCA studies of plant resource supply chains varies from one supply chain to another (Table 2). Moreover, the quantity of studies identified is not always directly related to knowledge of the environmental impact of the supply chain, for two reasons:

- ♦ the supply chain comprises a broad diversity of sub-chains for which few studies exist, or
- ♦ the number of quality studies of the option is insufficient.

Table 2 Studies identified and selected

	SUPPLY CHAIN	No. OF LCA REFERENCES INVENTORIED	No. OF LCA STUDIES (ESTIMATED)	No. of LCA STUDIES SELECTED
GROUP 1	Agrimaterials: • Fibre • Wood material	168: •36 •132	99: •17 •82	12: •5 •7
	Ether alcohols (biofuels)	213	145	9
	Ester oils (biofuels)	201	125	8
	Forest biomass [bioenergy; heat & electricity]	114	75	9
	Agricultural biomass [bioenergy; heat & electricity]	75	54	5
GROUP 2	Biopolymers	40	27	9
	Surfactants	26	13	6
	Hydraulic oils and lubricants	27	11	4
	Solvents	9	6	3
	Chemical and Other Intermediates	11	7	2
	Total	884	562	67

3.2 *Quality of available LCA knowledge*

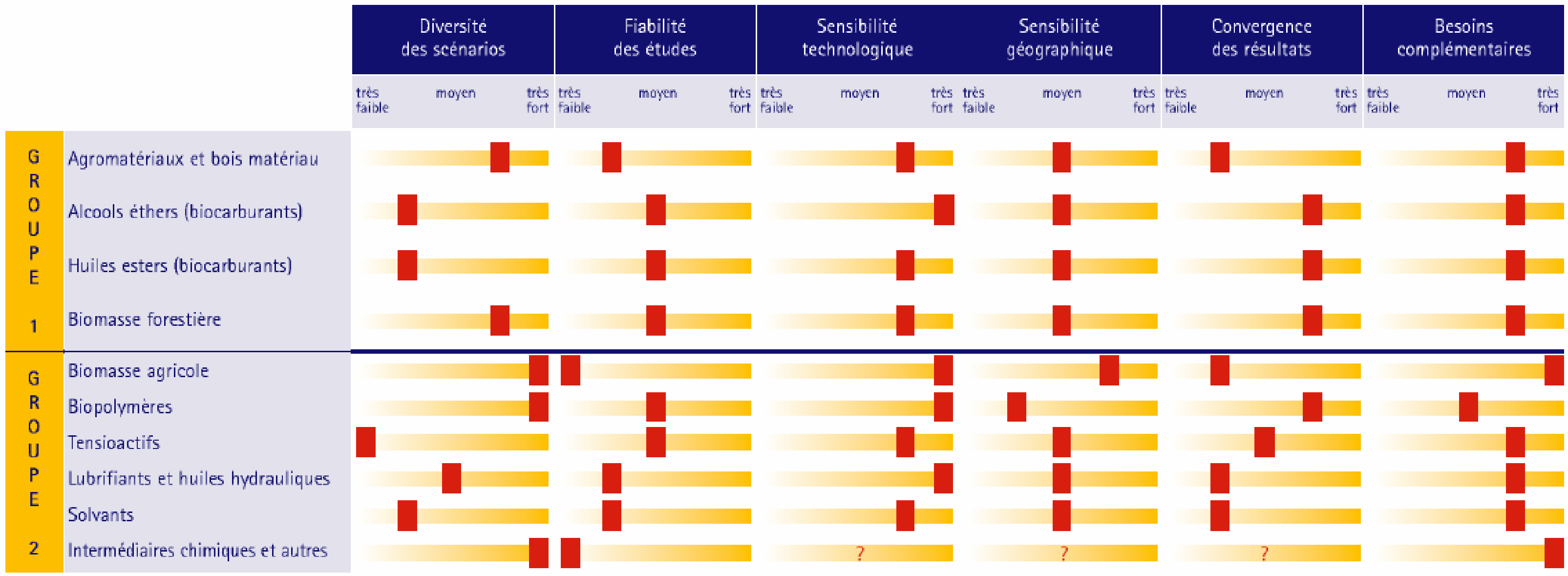
In the case of supply chains for which LCA studies are satisfactory, the trends observed are generally consistent. However, the numerical results may differ from study to study, depending on the basic data and the methodologies utilized.

The impact categories ("consumption of non-renewable primary energy" and "greenhouse effect") are relatively well known for all the supply chains in Group 1. Moreover, they have generally been more thoroughly studied than all other impact categories.

Table 3 Summary of the quality of LCA knowledge

Translation of column headings in Table 3

French term	*English translation*
Diversite des scenarios	*Range of scenarios*
Fiabilite des etudes	*Reliability of studies*
Sensibilite technologique	*Technological sensitivity*
Sensibilite geographique	*Geographic sensitivity*
Convergence des resultats	*Consistency of results*
Besoins complementaires	*Complementary needs*
Tres faible	*Very weak*
moyen	*Average*
Tres fort	*Very strong*


Diversité des scénarios
Fiabilité des études
Sensibilité technologique
Sensibilité géographique
Convergence des résultats
Besoins complémentaires
très faible
moyen
très fort
GROUPE 1
Agromatériaux et bois matériau
Alcools éthers (biocarburants)
Huiles esters (biocarburants)
Biomasse forestière
GROUPE 2
Biomasse agricole
Biopolymères
Tensioactifs
Lubrifiants et huiles hydrauliques
Solvants
Intermédiaires chimiques et autres
?

Range of scenarios

Based on the range of scenarios encountered in the various studies (with the exception of the chemical and other intermediates option, which is difficult to classify), two groups of options emerge:

- ♦ moderately weak to very weak range: supply chains where biomass is converted into a liquid product,
- ♦ moderately strong to very strong range: supply chains where biomass is converted into a solid product.

Reliability of studies

The bibliography available contains relatively few studies that are compliant with ISO 14040 to 14043 standards, except in the case of agrimaterials (particularly solid wood materials), biofuels and forest biomass [bioenergy; heat and electricity].

This means that many LCA results have not been subject to external review, particularly in the case of surfactants, hydraulic oils and lubricants, solvents, chemical and other intermediates, biopolymers and agricultural biomass [bioenergy].

Technological sensitivity

In terms of technological development, a major difference is observed between the various plant supply chains, some of which are still in the prototype stages, and conventional fossil fuel supply chains, in which technological development began many years ago. As a result, the gain offered by plant supply chains is not always maximized because these supply chains have not been technologically optimized.

However, while the technological sensitivity in the case of plants as a whole ranges from moderate to very strong, progress remains to be made. Indeed, a number of the major parameters that characterize these supply chains are technological in nature and therefore offer a valid means of improving their environmental performance.

Geographic sensitivity

Unlike the technological sensitivity, the geographic sensitivity is largely moderate for plant supply chains as a whole. It is most notable in the agricultural production phase, and more rarely in the conversion and processing phases.

Consistency of results

The consistency of results is highly variable, depending on the supply chain and impact categories. It is strongly linked to the quantity and reliability of studies available and to the diversity of the plant supply chain.

The variations seen in certain impact categories can be explained by:

- differences in LCA methodology among the various studies (boundaries of the system studied, methods of impact assessment, etc.),

- uncertainties related to specific pollutant emissions data, knowledge of the agricultural production phase and biomass conversion processes.

Finally, the consistency of results correlates substantially with technological knowledge of the supply chain; the exception is the case of surfactants, for which technological knowledge is satisfactory, but LCA knowledge is limited.

Complementary needs

Important LCA data requirements have been identified (details in the information sheets on supply chains, Chapter 7). They vary from one supply chain to another and result from:

- lack of complete LCA studies of supply chains that are well understood from the technological point of view (failure to take all impact categories into account, problems with the selection of appropriate functional units, failure to take the complete life cycle into account, etc.),

- lack of up-to-date LCA studies of supply chains that are undergoing technological development (an update is required).

4 *Environmental Balance Sheet: Plant vs. Fossil Resources*

For this comparison, two types of analyses have been chosen (cf. Chapter 6.3).

4.1 *Comparison by functional unit*

The first type of analysis treats environmental gains in relative terms. The impacts of plant resource supply chains are compared with those of fossil resource chains on the basis of a functional unit (FU), i.e. for the same service. For example, for one megajoule of useful energy, substituting an ethanol-based biofuel for gasoline allows for a 51 to 64 percent reduction in related greenhouse gas emissions.

When a product is composed of several materials and part of the product is replaced by a plant component, it is important to report the gain as a fraction of the product that has actually been replaced.

$$\text{relative gain or loss} = \frac{\text{Impacts [Fossil - Plant]}}{\text{Fossil replaced}} \; \%$$

The ranges in relative gain reported by the various studies are presented in the following figures (Figure 1, Figure 2).

Translation of terms on Figure 1 axes

Y-axis: *Relative gain or loss in %*
X-axis: *Agrimaterials, Biopolymers, Agricultural biomass [bioenergy], Forest biomass [bioenergy], Ether alcohols (biofuels), Ester oils (biofuels), Hydraulic oils and lubricants, Surfactants, Solvents*

Translation of terms on Figure 2 axes

Y-axis: *Relative gain or loss in %*
X-axis: *Agrimaterials, Biopolymers, Agricultural biomass [bioenergy], Forest biomass [bioenergy], Ether alcohols (biofuels), Ester oils (biofuels), Lubricants and hydraulic oils and lubricants, Surfactants, Solvents*

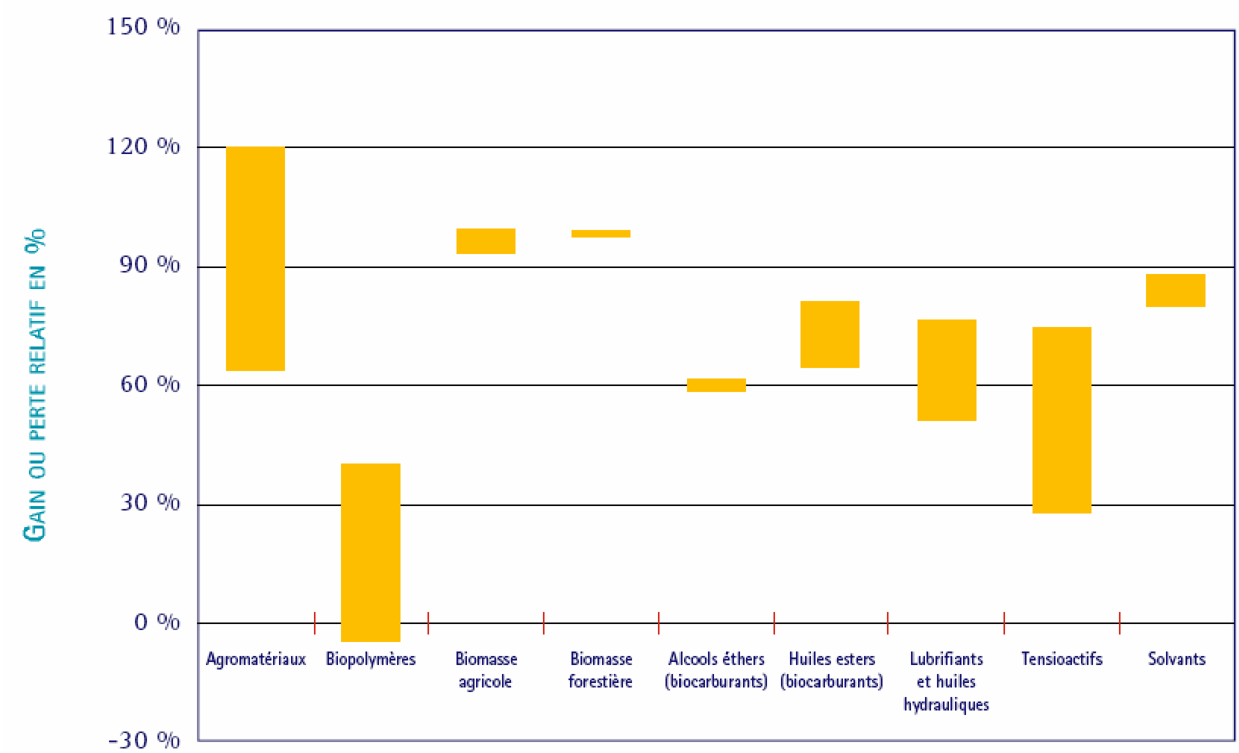


Figure 1
Plant/fossil comparison in terms of the "consumption of primary non-renewable energy" impact, per functional unit

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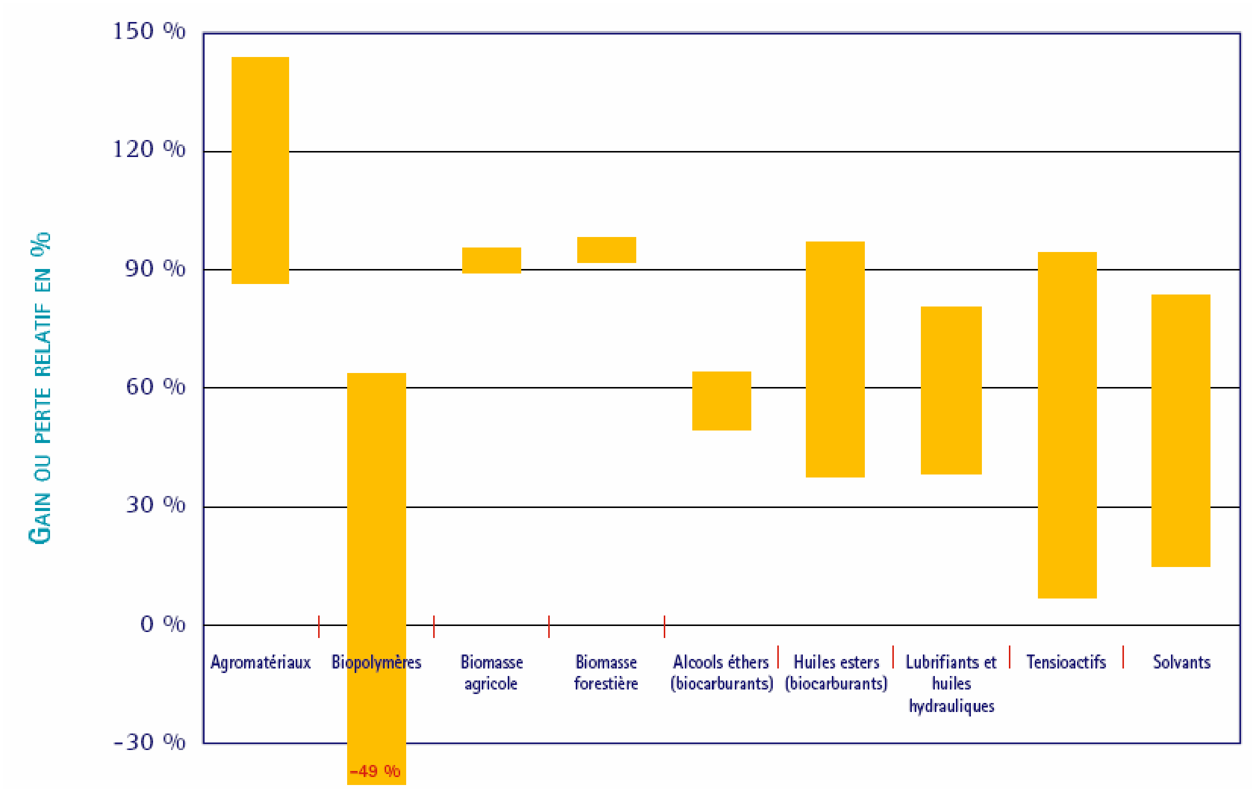

Figure 2
Plant/fossil comparison in terms of the "greenhouse gas emissions" impact, per functional unit

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Results:

- ♦ Agrimaterials, agricultural biomass [bioenergy; heat & electricity] and forest biomass [bioenergy; heat & electricity] show the highest relative gains in the "non-renewable primary energy" and "greenhouse effect" impact categories. In these sectors, less energy is required to manufacture the product than in the case of the other plant resource supply chains.

- ♦ The indirect benefits of agrimaterials (e.g. the benefit of weight reduction resulting from the use of plant fibres in car parts, cf. Chapter 4.3) greatly extend the environmental benefits of the supply chain and result in a gain in excess of 100 percent.

A fairly strong correlation exists between the benefits of the two impact categories ("non-renewable primary energy" and "greenhouse effect") except for supply chains where large quantities of hydro- or nuclear-generated electricity are used.

Representation by functional unit makes it possible to classify plant supply chains in three main groups according to relative gain in terms of consumption of non-renewable primary energy and impact on the greenhouse effect (Table 4).

4.2 *Comparison by functional unit and by unit area of farmland*

The second type of analysis produces a comparison in terms of absolute value. In this case, the difference in impact between fossil and plant supply chains is related to area of farmland. In the example of ethanol fuel (cf. Chapter 4.1), substitution results in a gain of 3.2 to 5.8 t CO_2 eq per hectare of value-added biomass.

absolute gain or loss =	$\frac{\textit{Impacts [Fossil - Plant]}}{\textit{Surface area}}$	*GJ/ha-yr, or t CO_2 eq/ha-yr*

The ranges in absolute gain reported are presented in the following figures (Figure 3, Figure 4).

Translation of terms on Figure 3 axes:

Y-axis: *Absolute gain or loss in primary GJ per functional unit and per hectare-year*
X-axis: *Agrimaterials, Biopolymers, Agricultural biomass [bioenergy], Forest biomass [bioenergy], Ether alcohols (biofuels), Ester oils (biofuels), Hydraulic oils and lubricants, Surfactants, Solvents*

Translation of terms on Figure 4 axes:

Y-axis: *Absolute gain or loss in t CO_2 eq per functional unit and per hectare-year*
X-axis: *Agrimaterials, Biopolymers, Agricultural biomass [bioenergy], Forest biomass [bioenergy], Ether alcohols (biofuels), Ester oils (biofuels), Hydraulic oils and lubricants, Surfactants, Solvents*

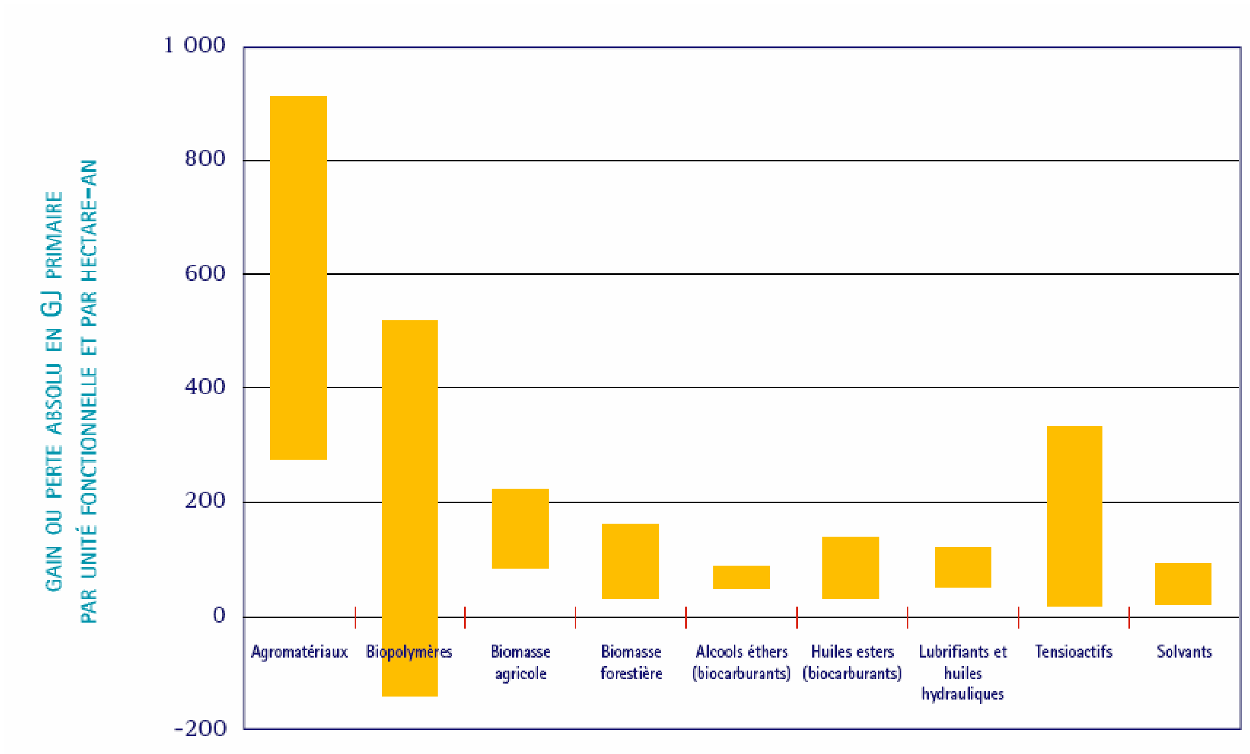

Figure 3
Plant/fossil comparison in terms of the "consumption of primary non-renewable energy" impact per functional unit and per unit surface area of cultivated land

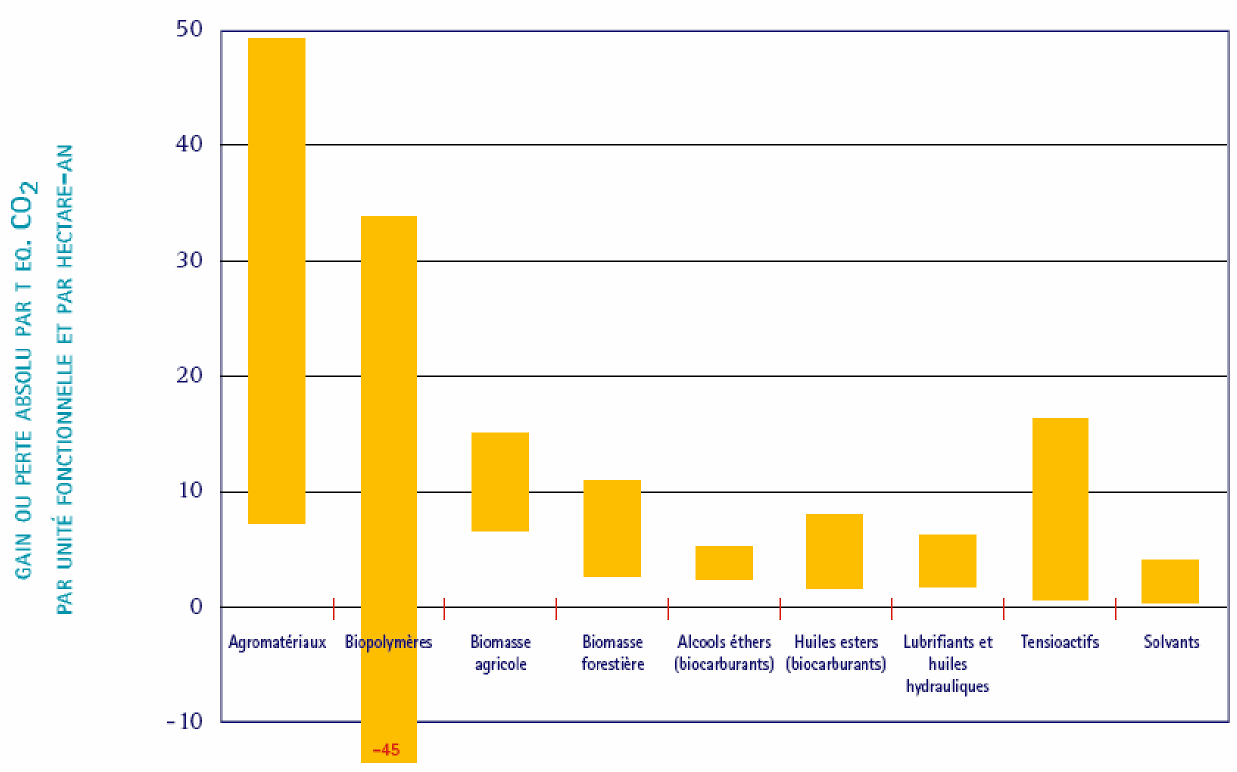

Figure 4
Plant/fossil comparison in terms of the "greenhouse gas emissions" impact per functional unit and per unit surface area of cultivated land

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Results:

- Agrimaterials and biopolymers (other than bacterial polymers) show the highest absolute gains in the "non-renewable primary energy" and "greenhouse effect" impact categories.

- As for the comparison in relative terms (cf. Chapter 4.1), the indirect benefits of agrimaterials (weight advantage, cf. Chapter 4.3) greatly extend the environmental benefits of the supply chain. They also result in a greater gain than what is obtained via the other plant supply chains.

Representation by hectare of cultivated land makes it possible to classify the supply chains in three main groups according to their potential to bring about a reduction in absolute terms in consumption of non-renewable primary energy and impact on the greenhouse effect (Table 4).

4.3 *Highlights*

Comparison of plant vs. fossil resource supply chains brings out several important, general lessons that are applicable to all the supply chains studied:

- No one plant resource supply chain stands out above all the others in all impact categories.

- Replacement of fossil fuels by plant supply chains reduces impacts related to "non-renewable primary energy consumption" and the "greenhouse effect," except in the case of bacterial polymers and certain applications that involve the use of other biopolymers.

- With regard to the "eutrophication" impact category, the LCA studies reviewed reveal the weakness of plant resource supply chains, with the exception of those based on the use of co-products.

- Most of the studies reviewed show that plant supply chains that produce chemicals have a weaker "acidification" impact than fossil fuel chains. Conversely, these same studies indicate that plant supply chains that produce energy have a greater "acidification" impact than the reference fossil fuel supply chains.

- The lack of data or poor data reliability, and the variety in units used prevent comparison of the supply chains in terms of the following impact categories: destruction of the ozone layer, photochemical pollution, terrestrial and aquatic toxicity, human health.

- Standardization of results on a European scale shows that gains in terms of non-renewable primary energy consumption and greenhouse gas emissions per hectare are slightly greater than variations in eutrophication and acidification in equivalent habitants.

Table 4 summarizes the findings, per hectare.

Translation of column headings in Table 4

French term	*English translation*
Filiere	*Supply Chain*
Gain relative au fossil substitute pour l'energie et l'effet de serre	Gain relative to fossil resources replaced, for non-renewable primary energy and greenhouse effect
Gain absolu par hectare pour l'energie et l'effet de serre	*Technological sensitivity* Absolute gain per hectare, for non-renewable primary energy and greenhouse effect
faible	*weak*
moyen	*average*
fort	*strong*

Table 4 Ranking of supply chains according to their relative and absolute gains in terms of "non-renewable primary energy" and "greenhouse effect" impacts.[5]

FILIÈRE[5]	Gain relatif au fossile substitué pour l'énergie et l'effet de serre[1]	Gain absolu par hectare pour l'énergie et l'effet de serre[2]
Agromatériaux[4]	fort	fort
Biopolymères	faible à moyen	faible à fort
Biomasse forestière	fort	moyen
Biomasse agricole	fort	moyen
Alcools éthers (biocarburants)	moyen	faible
Huiles esters (biocarburants)	moyen	faible
Lubrifiants et fluides hydrauliques	moyen	faible
Tensioactifs	moyen[3]	faible[6]
Solvants	moyen	faible

(1) *Strong benefit (gain exceeds 90%/FU); moderate benefit (gain of 50 to 90%/FU); weak benefit (gain less than 30%/FU).*
(2) *Strong benefit (gain exceeds 300 GJ/ha-yr or 20 t CO_2/ha-yr); moderate benefit (gain of 100 to 200 GJ/ha-yr or 5 to 10 t CO_2/ha-yr); weak benefit (gain less than 100 GJ/ha-yr or 5 t CO_2/ha-yr).*
(3) *Certain sub-chains may have gains below these levels.*
(4) *Because of the scarcity of comparative data, solid wood products are not included in this comparison.*
(5) *Not enough is known about the chemical and other intermediates sector, and it is too diverse (from the LCA perspective) to be included among these categories.*
(6) *Certain sub-chains may have gains in excess of these levels.*

Strong relative and absolute gains are possible with agrimaterials, particularly through the indirect advantages that greatly extend this supply chain's gains, for example, the reduction in vehicle weight that translates directly into lower fuel consumption.

Forest biomass [bioenergy] and agricultural biomass [bioenergy] supply chains offer strong relative gains associated with the low energy requirements for product manufacture. The absolute gain is moderate. It is slightly higher in the case of agricultural biomass [bioenergy] because of greater crop yield. However, combustion technology must be improved to lessen the impact of these two supply chains on human health.

The gain achieved from the biopolymer supply chain is highly variable and depends strongly on the application and the material that is substituted. Above all, the energy consumption of production processes and the quantity of material used per functional unit must be improved in order for biopolymers to be able to "compete" with their fossil counterparts (e.g. cushioning materials).

In the case of the other plant supply chains, the relative gain is moderate, and the absolute gain is weak. The explanation lies in the fact that, in the case of biomass, the upstream supply chain is sometimes longer and more complex than in the case of fossil resources. This is particularly true where biofuels are concerned.

The choice of functional unit and reference supply chain play an important role in the comparison. For example, certain products generated by the plant resource supply chain offer no significant inherent advantage in terms of environmental impact (per kilogram of product). However, for a given application, it is because smaller quantities of these products are used that they provide an environmental gain compared to their fossil counterparts.

Finally, this comparison is based primarily on two impact categories because reliable data on the other categories is lacking. However, in order for the comparison to be complete, all impact categories should be taken into consideration. This is the only way to produce a thorough comparison using life-cycle analysis methodology.

5 *Recommendations*

5.1 *Plant resource supply chains*

The following recommendations are intended to optimize the plant resource. However, constraints other than those of an environmental nature may create other priorities. For example, at present, there is no other solution to reduce CO_2 emissions in the transportation sector than to incorporate biofuels or reduce consumption.

Therefore, the following steps are recommended to optimize the development of plant resource supply chains:

- ♦ Focus on supply chains where the potential energy and greenhouse effect benefits are moderate to strong (agrimaterials, biopolymers, agricultural biomass [bioenergy] and forest biomass [bioenergy]), while taking exceptions into account.

- ♦ Emphasize supply chains in which the intrinsic characteristics of materials or energy from plant resources are superior to those of their fossil counterparts (resistance, weight, useful life, quantities required to perform the same function, etc.), and look for:

  - direct advantages (low energy requirement for product manufacture, less than or comparable to that of fossil resources, longer useful life for materials, etc.), and

  - indirect advantages (fuel economy resulting from vehicle weight reduction giving the plant resource supply chain greater than 100 percent advantage over fossil supply chain, cf. Chapter 4.1).

- ♦ Promote synergies among supply chains (use of co-products, etc.).

- ♦ Support technological improvement in all supply chains. Energy conversion is an important parameter, particularly for all energy applications. Technological improvement must therefore be a priority in the agrimaterials (fibres), biopolymers, forest biomass [bioenergy] and agricultural biomass [bioenergy] supply chains. With the exception of surfactants, plant resource supply chains are much less developed than their fossil counterparts, from both a technology and market share perspective.

Consistent integration of other factors that currently limit the development of plant resource supply chains, including market potential and economic viability, is also desirable.

5.2 *Improvement of LCA knowledge*

The environmental impacts of plant resource supply chains could be assessed by:

- broadening LCA knowledge in growth areas (strong potential in limited markets and/or moderate potential in larger markets) and improving quantification of environmental gains associated with the supply chains in question: collect missing LCA data and update obsolete data. Rapid technological growth of most plant resource supply chains means that part of the available data must be updated. Integration of logistic chains (long-distance transportation) receives little attention in the LCA studies and must also be a priority.

- using the LCA tool in R&D to invest in the most promising plant supply chains.

- extending the LCA tool to other limiting factors, e.g. to a link to an economic study (cost cycle analysis) and to a study of the potential for substitution on a market scale.

6 *Methodology*

6.1 *Bibliographic study*

An exhaustive international bibliographic study was conducted. The authors gathered post-1998 LCA studies on the ten plant supply chains concerned in order to review them in light of current international standards (post 1997, when the ISO 14040 standard was published). However, where no recent data were available, certain pre-1998 studies were used. In order to extract as much detail as possible from the documents on each sector, information sources included discussions with prominent individuals and agencies in the sectors concerned, specialized media, databases (e.g. Web of Science), the Internet, etc.

6.2 *Analysis of study quality and selection*

A critical analysis was carried out of the studies identified from the selected bibliography. Only the most relevant in each sector were selected and then systematically and objectively evaluated according to a set of specific criteria.

6.3 *How to compare supply chains?*

The comparison of plant supply chains requires a new methodology. The objective is not to provide typical values for each chain (the state of current knowledge does not always allow for this), but to reveal certain trends based on available LCA studies. Two types of possible comparisons of plant resource supply chains are presented in this summary (Table 5).

Table 5 Advantages and limitations of comparisons between plant resource supply chains and their reference fossil resource counterparts

LEVEL OF COMPARISON	TYPE OF COMPARISON	ADVANTAGES	LIMITATIONS	RESULTS
All applications	Impacts [fossil - plant] per functional unit and per hectare	• Allows a comparison for all plant and fossil supply chains • Shows optimization of available agricultural areas	Adds further uncertainties (yield, quantity of plant material necessary per functional unit, co-products)	ABSOLUTE VALUE
All applications	Impacts [fossil - plant] / fossil product replaced per functional unit[2]	• Allows a comparison for all plant and fossil supply chains • Highlights products that use small amounts of non-renewable energy for product manufacture	Does not show absolute gain	RELATIVE VALUE (relative to fossil-derived product replaced)
By application[1]	Impacts [fossil - plant] per functional unit	Respects the system operation	Irrelevant to systems that have different functional units	ABSOLUTE VALUE

By material/energy[1]	Impacts [plant] and impacts [fossil] per kilogram or per megajoule of useful energy	Allows for easier comparison	Occasionally distorts the comparison (different quantities per functional unit)	

(1) This summary report does not provide a detailed account of these types of comparisons because they are not suited for a comparison of different supply chains.
(2) Cf. Chapter 4.1.

Depending on whether the use of available agricultural areas is taken into account, two types of comparisons may be presented (Table 5):

- Comparison of relative gains makes it possible to identify supply chains and products that require little energy for product manufacture (cf. Chapter 4.1, Figure 1, Figure 2).

- If the use of available agricultural area is optimized, a comparison of absolute gains per functional unit and per hectare of cultivated land is clearly preferable to a comparison of relative gains (cf. Chapter 4.2, Figure 3, Figure 4). For example, biofuels produced on all available farmland in France could not replace all the fossil fuels used in country.

N.B.: The ranges of values observed in this comparison cannot and must not be used as reference values or as averaged values. In fact, the ranges of values do not reflect the uncertainty of the environmental impacts associated with plant supply chains, but depend on the diversity of the supply chains and available LCA studies.

6.4 *Reporting format*

The methodology used to review current LCA studies of plant supply chains led to the production of three types of documents. In order: information sheets covering LCA studies, information sheets covering different supply chains, a comprehensive comparative summary.

- One information sheet per LCA studies: one sheet was prepared for each study, except in the case of reviews, which, strictly speaking, are not LCA studies.

- One information sheet per supply chains: an initially detailed structure is followed by a summary format; results are presented for each supply chain studied (cf. Chapter 7).

- External expertise: the work of BG Ingénieurs-conseils and the EPFL was validated by ADEME experts. Other recognized experts in the various supply chains were also consulted (industrialists, research laboratories).

- ♦ Comprehensive summary: based on the state of current LCA knowledge of the ten plant supply chains and the comparison of them. The results identified were summarized in a three-level analysis (from general to detailed):
  1st level: supply chain information sheets - general
  2nd level: supply chain information sheets - detailed
  3rd level: bibliographic sheets for each LCA study

These results are available on the Internet at: www.ademe.fr/agrice (under "Publications").