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# A review of the sustainability of algal-based biorefineries: Towards an integrated assessment framework

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A B S T R A C T

Algal-based bioenergy products have faced multiple economic and environmental problems. To counter these problems, algal-based biorefineries have been proposed as a promising solution. Multiple environmental and economic assessments have analyzed this concept. However, a wide variation in results was reported. This study performs a review to evaluate the methodological reasons behind this variation. Based on this review, four main challenges for a sustainability assessment were identified: 1) the use of a clear framework; 2) the adaptation of the methodology to all stages of technological maturity; 3) the use of harmonized assumptions; 4) the integration of the technological process. A generic methodology, based on the integration of a techno-economic assessment methodology and a streamlined life cycle assessment was proposed. This environmental techno-economic assessment can be performed following an iterative approach during each stage of technology development. In this way, crucial technological parameters can be directly identified and evaluated during the maturation of the technology. The use of this assessment methodology can therefore act as guidance to decrease the time-to-market for innovative and sustainable technologies.



**Contents**



*Abbreviations:* TEA, Techno-Economic Assessment; TRL, Technology Readiness Level; LCA, Life Cycle Assessment; LCC, Life Cycle Costing; GWP, Global Warming Potential; ETEA, Environmental Techno-Economic Assessment

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## 1. Introduction

Algal-based biorefineries have been proposed as a promising approach to enhance the microalgae industry. The valorization of multiple co-products could improve the economic viability of microalgal-based biofuels [1]. However, further investigations concerning the economic feasibility and the environmental impact are required [2]. Multiple studies have performed economic or environmental assessments in order to accurately quantify these impacts. The main objective of this study is to propose a new methodology, which can harmonize the different assessments from a methodological point of view. Such a harmonized assessment enables the comparison of the different proposed production processes to permit a clear view on the commercialization potential of microalgae-based biorefineries.

Microalgae are photosynthetic microorganisms that can be found in all existing ecosystems [3]. A study by Guiry [4] estimated the total amount of algal species to be 72,500. Due to this large variety in species, multiple applications exist, such as food, feed and energy [5]. However, only approximately 15 species of microalgae are currently used on a commercial level. Therefore, microalgae are still considered as an untapped resource for a biobased economy [6].

Compared to other bioenergy feedstocks, microalgae have a large biomass productivity and high lipid content [7]. Therefore, the application of microalgae biofuels has gained a lot of attention during the last decades [8,9]. However, several economic and environmental constraints concerning its commercialization have been identified; examples are the high production costs compared to fossil fuels and the high water consumption during cultivation [10,11]. Moreover, the production of biofuels in general has become controversial, for instance due to the food-versus-fuel debate and indirect land-use change emissions. If the biofuel industry cannot ensure that its environmental impact is significantly lower than that of the fossil fuels it substitutes, the main reason of existence for this industry is at risk [12].

A solution to these environmental and economic problems of biofuels could be the supplementary valorization of other biochemical components from the microalgae biomass [1]. This algal-based biorefinery perspective has been suggested by multiple authors [13,14]. Also other biomass feedstocks have been discussed for the application of a biorefinery concept [15]. The algal-based biorefinery should follow the cascading principle, which prioritizes the production of high-value products before energy products [16]. The sustainability of this concept has been examined by multiple studies, in order to prevent the problems that slowed down the research and development of algal biofuels. Multiple authors have emphasized the need for harmonization efforts as the results of these economic and environmental assessments are widely varying [17,18]. Such a harmonization study was performed by Sun et al. [19] in order to decrease the variability in production costs between 12 economic studies. The authors concluded that the variety could be attributed to disparate assumptions and uncertainties in economic and process inputs. The differences in process inputs have been reviewed by multiple studies, such as Williams and Laurens [20]. However, only a few papers, such as Collet et al. [17], reviewed the disparate methodological assumptions in depth. Moreover, most of these reviews were limited to one dimension of sustainability. Harmonization efforts between a techno-economic and environmental assessment of algal-based biofuels have been undertaken in order to enable the study of tensions and tradeoffs between the different sustainability dimensions [21]. However, an in-depth review, including the integration of these different dimensions, is still lacking.

This paper fills this gap by reviewing the methodologies used to assess the sustainability of algal-based biorefineries. The different methodological choices and assumptions are discussed in order to identify the main methodological reasons for the varying results. This review generates four main challenges for a harmonized and integrated methodology. Based on these challenges, a generic integrated assessment of the sustainability of algal-based biorefineries is proposed. This strategy was illustrated in Fig. 1.

## 2. Methodology

This review covers quantitative sustainability assessments from an environmental, an economic and a combined perspective. No papers were encountered which examined the social aspects of algal-based biorefineries; therefore, this dimension could not be included. The assessments included in this review originate from scientific peer-reviewed articles found in different scientific databases (EBSCOHOST and Google Scholar).

Sixty-four environmental assessments, forty economic assessments and twenty assessments, which combined or integrated both dimensions, were included. The methodology used for the assessments was reviewed in detail, focusing on the framework of the methodology itself, the scope of the assessments, the inclusion of uncertainties, the assumptions and the static or dynamic character of the technological process, which was assessed. Based on the differences between the different assessment methodologies on all these categories, four main challenges with which the different studies have to deal with are identified. Three of these challenges are directly related to the differences between the different studies within one sustainability dimension. The fourth

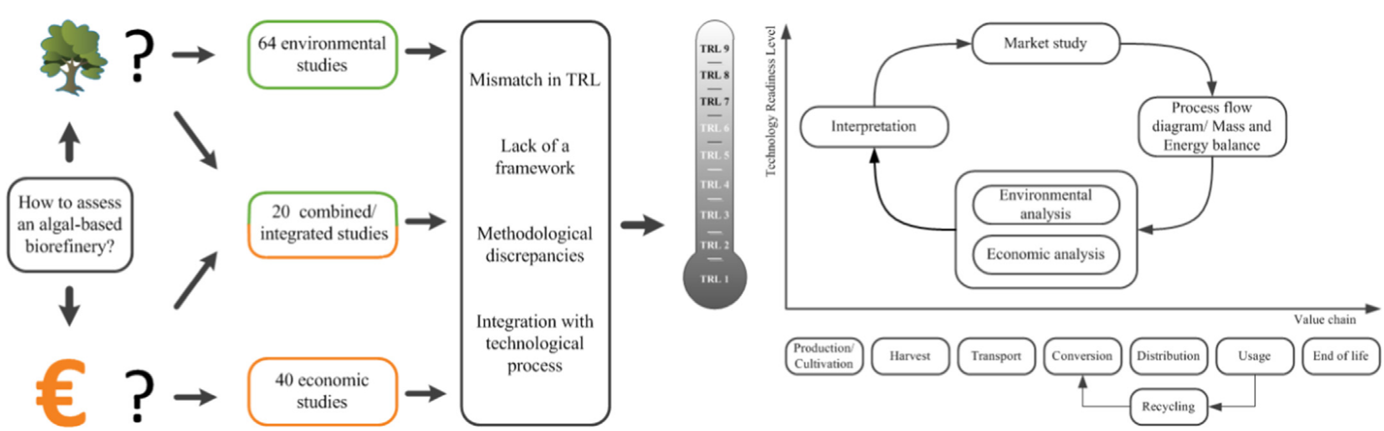


**Fig. 1.** Graphical abstract of this study.

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challenge is linked to the harmonization and integration efforts between the different sustainability dimensions.

The reviewed papers cover a period of six years, from January 2009 to January 2015. All papers have a general biorefinery perspective. A general biorefinery was previously defined as “a facility (or a network of facilities) that integrates biomass conversion processes to produce fuels, power and chemicals from biomass” [22,23]. Therefore, by definition a biorefinery adopts a multi-product perspective based on biomass. This review will focus on the sustainability assessments of microalgal-based facilities which produce more than one product, but is not restricted to the combination of energy and materials. Therefore, an assessment, covering a production plant which only produces fuel, power or chemical products was also included. As these studies encounter the same problems as algal-based biorefineries which do produce a combination of energy and materials, this broader perspective on the algal-based biorefinery concept was adopted. Outputs, which were considered to be waste, were not defined as a product.

More technologically oriented reviews of sustainability assessments can be found in the studies of Quinn and Davis [18], Benemann et al. [24] and Collet et al. [17]. Therefore, this review will focus on methodological differences and only briefly discusses technological aspects. However, the lack of a detailed engineering design and system analysis has been identified as a crucial problem to sustainability assessment methodologies [24]. The degree of integration of the technological process is therefore included in this review. Three levels of integration are identified: (1) no technological assessment, (2) combined technological and environmental/economic assessment, and (3) integrated technological and environmental/economic assessment. If there is no technological assessment combined or integrated in the assessment, the technological input parameters are based on the literature of different processes. No common technological process from feedstock to end-product is defined. If the technological assessment is combined, the analysis of a process chain from feedstock to end-product is included. In this case, the environmental or economic assessment is performed in an independent manner. Outputs from the technological assessment are used as static values in the environmental or economic assessment. If the technological assessment is integrated, the environmental or economic assessment is directly linked to dynamic process parameters. A change in process parameters will have a direct influence on the environmental or economic feasibility. The classification of the different studies in accordance with these three categories was made based on the content of the respective paper.

## 3. Results

The methodological variation in the reviewed environmental assessments is displayed in Table 1. The main assessed environmental impacts for algal-based biorefineries are the energy consumption and the greenhouse gas emissions. The majority of the studies conclude that microalgae have lower greenhouse gas emissions compared to conventional fuels [24]. However, the exact greenhouse gas emissions reported vary widely [18]. The recycling of nutrients, water and energy has been suggested to reduce the resource and energy consumption [25–27]. Other technologies with the same purpose that were included in the studies are the use of wet extraction methods and the use of brackish, saline or wastewater [28,29]. However, due to the high methodological variation of the environmental assessments, it is not possible to draw a generic conclusion over the environmental impacts of algal-based biorefineries.

The economic feasibility of algal-based biorefineries is mainly dependent on the production costs of the algal biomass [10]. The largest contribution originates from the supply of resources, such as nutrients, $CO_2$ and water; labor and overhead costs, and the construction and operation of the cultivation and harvesting system [14,88,90]. Subsidies and taxes also play an important role [91]. In general, the use of photobioreactors is much more expensive than the use of open raceway ponds [29,92]. Most studies remain focused on biofuels and do not fully incorporate the economic potential of the coproducts. Economies of scope due to the commercialization of coproducts may enable an increase in revenues, and therefore an increase of the overall economic feasibility [72]. However, in accordance with the environmental assessment, no general conclusion can be made yet concerning the economic viability of algal-based biorefineries. The methodological variation of the reviewed economic assessments is displayed in Table 2.

Based on Tables 1 and 2, the variation in results between the different impacts assessment studies can be explained by three main reasons related to the assessment methodology: (1) the framework methodology, (2) a mismatch in the Technology Readiness Level (TRL) of the technology and the required TRL for the methodology, and (3) methodological discrepancies.

### 3.1. Framework methodology

The lack of a generic framework or the inconsistent following of its predefined guidelines is identified as the first reason for the assessments to render varying results.

Most of the environmental studies aimed at performing a Life Cycle Assessment (LCA). An LCA is defined as “the compilation and evaluation of the inputs, outputs, and potential environmental impacts of a product system throughout its life cycle” [109]. The life cycle starts from the extraction of resources, moving through the production of materials, the process itself, the use of the product, and ends with the reuse, recycle or disposal phase [110]. Although there is no single method to perform an LCA, clear guidelines were stated in the ISO LCA standards to enable a harmonized generic framework based on the four predefined steps [109]. These four steps enable the clear illustration of the methodological strategy. An example of this asset can be found in the study by Weinberg et al. [36]. These four main steps were only encountered in 18 of the 48 environmental studies which aimed to perform an LCA. Although ignoring this framework does not necessarily mean that the environmental study is of a lesser quality, the advantage of a generic harmonized framework provided by the LCA is lost.

Three economic studies aimed at a Life Cycle Costing (LCC) for their assessment. A LCC captures all costs endured during the life cycle of a product; it can include external costs such as environmental costs and social costs. Upstream financial costs are automatically included in the price of inputs, so upstream activities do not need to be considered [111]. Therefore, a LCC shares the same scope and timeframe as an LCA, so the LCA framework can also be used by the LCCs. However, only Meyer and Weiss [94] followed the predefined steps of the LCA framework. No other economic studies used a generic framework for their assessment.

### 3.2. Technology Readiness Level (TRL)

The second reason for the varying results is related to the early TRL of algae-based biorefineries. The TRL scale is a classification scale for the maturity of a specific technology [112]. As there are currently no commercial algae-based biorefineries, this technology is in an early TRL stage, where data for the entire process is not yet available. Therefore, the assessments have a prospective nature, rather than a retrospective one.

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**Table 1**
Overview of environmental assessment literature on microalgae-based biorefineries.

| Fw[a] | Ref[b] | App.[c] | SB[d] | Spat.[e] | Time[f] | Waste[g] | Imp[h] | | | | | FU[i] | All[j] | SA[k] | Int[l] |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | CC | En | W | Eu | OI | | | | |
| LCA | [30] | | Cr*–Gr* | C | I,F | X | X | $F^{l}$ | X | | | M | S,Ec | L | Int |
| LCA | [31] | | Cr*–Gr* | C | I,F | X | X | $F^{l}$ | X | | | M | S,Ec | L | Int |
| LCA | [32] | | Cr*–Gr* | C | F | | X | $F^{l}$ | | X | X | $En^{l}$ | S, $En^{l}$ | | Comb |
| LCA | [33] | Att | Cr–Gr* | R | I,F | X | X | $F^{h}$ | X | X | X | M,$En^{h}$ | Ec | L | Comb |
| LCA | [34] | | Cr–Gr* | R | | | X | $X^{h}$ | | | | M | $En^{h}$ | L | Comb |
| LCA | [35] | | Cr–Gr* | C | I | | X | $F^{l}$ | | | | $En^{l}$ | S | | Comb |
| LCA | [36] | | Cr–Gr* | R | I | | X | | | | | $En^{l}$ | $En^{l}$ | L | Int |
| LCA | [37] | | Cr–Gr | C | | X | X | F | | X | X | En | M,En | L | Comb |
| LCA | [38] | | Cr–Gr | R | P | | X | $F^{l}$ | | | X | M | S,Ec | L | Comb |
| LCA | [39] | | Cr–Gr | C | | X | X | $X^{h}$ | X | | X | $En^{h}$ | $En^{h}$,S | L | Comb |
| LCA | [40] | | Cr–Ga | R | P,I | | X | $F^{l}$ | | X | X | F | | L | Int |
| LCA | [41] | | Cr*–Ga | R | F | X | X | $X^{h}$ | X | X | X | $En^{h}$ | Ec | G | Int |
| LCA | [42] | | Cr*–Gr | C | F | | X | $F^{h}$ | | | | $En^{h}$ | S | G | Int |
| LCA | [43] | | Ga–Ga | R | | | X | $X^{h}$ | | | | $En^{h}$ | M | | Comb |
| LCA | [44] | | Cr–Ga | C | | X | X | X | X | | X | En | S | L | Int |
| LCA | [45] | | Ga–Ga | C | I,F | X | X | | | | | V | | L | Int |
| LCA | [46] | | Cr–Ga | C | | X | X | | | | | M | S | | Comb |
| | [28] | | Cr*–Gr* | C | I,F | | X | $F^{l}$ | | | | $En^{l}$ | $En^{l}$ | G | Int |
| | [47] | | Cr*–Gr* | R | I,F | X | X | $X^{l}$ | X | X | | F | S | L | Int |
| | [48] | | Cr*–Gr | C | I,F | X | X | $F^{l}$ | | | | $En^{l}$ | $En^{l}$ | G | Int |
| | [49] | Att | Cr*–Gr | C | I,F | | X | $X^{l}$ | X | X | X | $En^{l}$ | $En^{l}$ | L | Comb |
| | [29] | | Cr*–Gr | C | F | X | X | $X^{l}$ | X | X | | F | S | G | Int |
| | [50] | | Cr*–Gr | | F | | X | | | X | X | $En^{l}$ | $En^{l}$ | G | Int |
| | [51] | | Cr–Gr | S | F | X | X | $F^{l}$ | X | | | $En^{l}$ | S | L | Int |
| | [52] | | Cr–Gr* | R | | | X | $X^{l}$ | X | | | F | M/En | G | Int |
| | [53] | | Cr–Gr* | R | | X | X | $X^{l}$ | | | | V | Nc | L | Int |
| | [54] | | Cr–Gr* | | | | X | $F^{l}$ | | | | $En^{l}$ | $En^{l}$ | G | Int |
| | [55] | | Cr–Gr | | | | X | $F^{l}$ | | | X | $En^{l}$ | $Hy^{l}$ | L | Int |
| | [56] | | Cr–Gr* | C | F | X | X | $X^{h}$ | | | | M | | | Int |
| | [57] | | Cr–Gr | R | | | X | $X^{l}$ | | | | $En^{l}$ | $En^{l}$ | L | Int |
| | [58] | | Cr–Gr | C | | | X | | | | | $En^{l}$ | $En^{l}$ | G | Int |
| | [59] | | Cr*–Ga | | | | X | X | X | X | X | M | M | | |
| | [60] | | Cr*–Ga | R | I,F | | X | X | | X | | F | S | G | Int |
| | [61] | | Cr*–Ga | R | F | | X | $F^{l/h}$ | | | | $En^{l}$ | S | L | Int |
| | [62] | | Cr*–Ga | R | | | X | | | | | P | S | L | Int |
| | [63] | | Cr*–Ga | | F | | | $F^{h}$ | | | X | M | $En^{h}$ | L | Int |
| | [64] | | Cr*–Gr* | R | F | | | $X^{h}$ | X | | X | $En^{h}$ | $En^{h}$ | | Int |
| | [65] | | Cr–Ga | S | | | | | X | | X | $En^{l}$ | S/$En^{l}$ | L | Int |
| | [25] | | Cr–Ga | | | | X | $F^{l}$ | X | | | M | S | L | Int |
| | [66] | | Cr–Ga | R | I | | X | X | X | | | En | S/Ec | L | Comb |
| | [67] | | Cr–Ga | | | | X | $X^{h}$ | | X | | M | S | | Comb |
| | [68] | | Cr–Ga | S | | | X | $X^{l}$ | X | | X | V | S | G | Int |
| | [69] | | Cr–Ga | R | F | | X | $X^{l}$ | | | | $En^{l}$ | S,En,Ec | L | Int |
| | [70] | | Cr–Ga | S | I | | X | $X^{l}$ | | | | M,Ec,$En^{l}$ | Ec,M | L | Int |
| | [71] | | Ga–Ga | R | | | X | | | | X | T | S | L | Comb |
| | [72] | | Cr–Ga | | I,F | X | X | | | | | M | S,Ec | | Int |
| | [73] | | Cr–Ga | R | | X | X | | | | | T | S | L | Int |
| | [74] | | Cr–Ga | C | | | | | X | | | M | M | | Int |
| | [75] | | Ga–Gr | C | | X | X | X | | X | X | M | NC | L | Comb |
| | [26] | | Ga–Gr | S | I | | X | X | | | | En | S | | Comb |
| | [76] | | Ga–Gr | C | F | | X | F | | | | En | | L | Comb |
| | [77] | | Ga–Ga | C | F | X | X | X | | | X | M | | | Comb |
| | [78] | | Ga–Ga | C | | | X | $X^{l}$ | | | | $En^{l}$ | Ec | L | Comb |
| | [79] | | Ga–Ga | R | | | X | | | | X | $En^{l}$ | | | |
| | [80] | | Ga–Ga | | I,F | X | X | | | | | T | | | Int |
| | [81] | | Ga–Ga | C | I | | X | | | | | V | En,S | | |
| | [82] | | Ga–Ga | C | I,F | X | X | | | | | V | | | Int |
| | [83] | | Ga–Ga | | | X | | Ex | | | | | Ex | | Int |
| | [84] | | Ga–Ga | | | X | | Ex | | | | | Ex | | Int |
| | [85] | | Ga–Ga | | | | | X | X | | | V | | | Int |
| | [86] | | Ga–Ga | | | | | X | X | | | V | | | Int |
| | [87] | | Ga–Ga | | | | | X | X | | | V | | L | Int |
| | [88] | | Ga–Ga | R | | X | | $X^{h}$ | X | | | T | | | Int |
| | [89] | | Ga–Ga | | | | | | X | | | En | | L | |

[a] **Fw** = Framework. LCA: Life Cycle Assessment.
[b] **Ref** = Reference number.
[c] **App.**=Approach. Att: Attributional.
[d] **SB** = System boundaries. Cr: Cradle; Cr*: Cradle (+ infrastructure); Ga: Gate; Ga*: Gate (+ Infrastructure), Gr: Grave; Gr*: Grave (+ coproducts).
[e] **Spat.**=Spatial scale. C: Country-specific; R: Region-specific; S: Site-specific.
[f] **Time** = Time horizon. I: Defined for the impact (GWP); E: Defined for the equipment; P: Defined for the project.
[g] **Waste** = Inclusion of waste streams.
[h] **Imp** = Impact category. CC: Climate change; En: Energy; W: Water; Eu: Eutrophication; OI: Other indicator; X: Total energy; F: Fossil energy; Ex: Exergy; l: Lower heating value; h: Higher heating value.

[i] **FU** = Functional unit. En: Energy; M: Mass; T: Time; F: Functional; V: Volume; Ex: Exergy; Ec: Economic; Hy: Hybrid; l: Lower heating value; h: Higher heating value.
[j] **All** = Allocation. S: Substitution; M: Partitioning based on mass; Ec: Partitioning based on economic value; En: Partitioning based on energy; Nc: Not clear l: Lower heating value; h: Higher heating value.
[k] **SA** = Sensitivity assessment. G: Global sensitivity analysis; L: Local sensitivity analysis.
[l] **Int** = Integration of technological assessment. Int: Integrated technological and environmental assessment. Comb: Combined technological and environmental assessment.

**Table 2**
Overview of economic assessment literature on microalgae-based biorefineries.

| Goal[a] | Ref[b] | FU[c] | Waste[d] | Loc.[e] | Depr (yrs.)[f] | Ind[g] | Time (yrs.)[h] | Disc (%)[i] | T/S[j] | Sc (P)[k] | Sc (T)[l] | Imp[m] | SA[n] | Int[o] |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **RA** | | | | | | | | | | | | | | |
| | [89] | T | | | | | 1 | | | | | Rev | | |
| **CA** | | | | | | | | | | | | | | |
| | [79] | En | X | R | 15,50 | X | 13 | 2,5,8 | | 1 | | IC | L | |
| | [93] | M | | R | 10 | X | 1 | 8.5 | | 1 | | Pr | G | Int |
| | [56] | T | X | C | 20 | X | 1 | | | 1 | IR | Pr | | Comb |
| | [87] | V | | | | X | | | | 1 | | Cost | L | Comb |
| | [81] | P | | C | Ns | X | | 7 | T | 0.6–0.8 | Inx | IC | G | |
| **LCC** | | | | | | | | | | | | | | |
| | [94] | En[l] | X | R | 10,20 | X | 1 | Ns | | 0.8–0.9 | IR | Cost | L | Int |
| | [29] | F | X | R | 11 | X | 30 | 5,10,15 | T | 1 | IR | Pr | G | Int |
| | [60] | P | | R | 7 | X | 20 | 5,10,15 | T | Nc | | IC | L | Int |
| **FA** | | | | | | | | | | | | | | |
| | [92] | P | X | | 5% | X | 10 | 10 | T | 1 | IR | IC | G | Int |
| | [91] | P | | R | 16 | X | 20 | 10 | T,S | 1 | IR | IC | L | |
| **EA** | | | | | | | | | | | | | | |
| | [78] | M | | C | | | | | | 1 | | Cost | | Comb |
| | [20] | T | | C | 10 | X | 1 | | | 1 | IR | Pr | L | Int |
| | [40] | F | | R | Ns | | 1 | | S | Reg | Inx | Pr | L | Int |
| | [75] | | | C | | | | | | 1 | | Pr | | Comb |
| | [85] | V | | | Ns | X | | | | 1 | Ns | Pr | L | Int |
| | [86] | T | | | Ns | X | | | | 1 | Ns | Pr | | Int |
| | [95] | P | | C | Ns | X | 35 | 3.5 | T | 1 | Inx | IC | L | Comb |
| | [96] | P | X | R | Ns | X | 30 | 7,15 | T | 1 | Ns | IC | G | Int |
| | [76] | P | | C | 10 | X | 10 | 7.5 | T | 1 | | IC | G | Int |
| | [97] | P | | | 20 | | 20 | 9.95 | S | 1 | IR | IC | L | Int |
| **TEA** | | | | | | | | | | | | | | |
| | [80] | T | X | | 20 | X | 20 | 12 | | 0.3–0.8 | Inx | Pr | L | Int |
| | [72] | T,V | X | C | 20 | X | 20 | 10 | | 0.4–1 | Inx | Pr | | Int |
| | [62] | V | | R | Ns | X | 1 | | T | 1 | | Pr | L | Int |
| | [98] | V | | S | | X | 30 | | | 1 | | Cost | L | Int |
| | [99] | V | | S | | | | | | 1 | | Cost | L | Comb |
| | [100] | V | X | R | 7 | X | 20 | 10 | T | 1 | Ns | Pr | L | Comb |
| | [88] | V | X | R | 10,20 | X | 10,20 | | | 1 | | Cost | L | Int |
| | [82] | V | X | C | 20 | X | 20 | 10 | | 0.6–1 | Inx | Pr | | Int |
| | [101] | V | | R | | | | | | 1 | Inx | Pr | | Comb |
| | [102] | V | X | C | 7,20 | X | 30 | 10 | T | 0.6 | Ns | IC | G | Int |
| | [103] | V | X | S | 7 | X | 30 | 10 | T | 0.6 | Inx | IC | L | Comb |
| | [90] | V | | C | 25 | X | 25 | 10 | | 1 | Inx | Cost | L | Comb |
| | [104] | V | X | C | 7 | X | 20,30 | 10 | T | 1 | | IC | L | Int |
| | [45] | P | | C | Ns | X | Ns | Ns | T | 0.3–0.8 | Inx | IC | L | Int |
| | [105] | P | X | | 20 | X | 20,30 | 5,10 | S | 1 | IR | IC | L | Comb |
| | [77] | T | X | C | 10 | X | 10 | 16 | T | 1 | IR | IC | L | Comb |
| | [106] | P | | C | RBM | X | 15 | 15 | S,T | 0.7–0.9 | | IC | L | Int |
| | [107] | P | | | | | | | | 1 | | IC | L | Int |
| | [108] | P,M | | C | 5% | X | 30,5 | | T | 0.8 | IR | IC | G | Int |

[a] **Goal.** RA: Revenue assessment; CA: Cost assessment; LCC: Life Cycle Costing; EA: Economic assessment; FA: Financial assessment; TEA: Techno-economic assessment.
[b] **Ref** = Reference number.
[c] **FU** = Functional unit. En: Energy; M: Mass; T: Time; P: Project; F: Functional; V: Volume; l: Lower heating value.
[d] **Waste** = Inclusion of waste streams.
[e] **Loc.**=Location definition. C: Country scale; R: Regional scale; S: Selection of a specific location.
[f] **Depr (yrs.)** = Depreciation period in years. RBM: Reducing balance method; Ns: Period is not specified.
[g] **Ind** = Indirect costs (labor, overhead, …). Ns: Not specified.
[h] **Time (yrs.)** = Time span in years. Ns: Not specified.
[i] **Disc** (%) = Discounting factor in %. Ns: Not specified.
[j] **T/S**=Taxes and subsidies. T: Tax included; S: Subsidy included.
[k] **Sc(P)**=Sizing factor for the scale of the process. Nc: Not clear.
[l] **Sc(T)**=Temporal scale. Inx: Index; IR: Inflation rate; Ns: Not specified.
[m] **Imp** = Impact category. Rev: Revenue; Pr: Profit; IC: Investment criteria (for example, net present value, internal rate of return).
[n] **SA** = Sensitivity assessment. G: Global sensitivity analysis; L: Local sensitivity analysis.
[o] **Int** = Integration of technological assessment. Int: Integrated technological and environmental assessment. Comb: Combined technological and environmental assessment.

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Most environmental assessments aim at analyzing the total environmental impact of a product during all life cycle phases. For that reason, a complete range of environmental impacts needs to be included for all processes, inputs and outputs during the entire life cycle. Such large amount of data is only available in a late TRL stage. Therefore, a mismatch exists between the TRL level needed for the methodologies and the TRL level of the technology under assessment. The reviewed studies solve this mismatch by streamlining their assessment methodology to reduce the data requirement. Three different streamline approaches have been followed: (1) excluding certain life cycle phases, (2) reducing the number of environmental impact categories, and (3) using surrogate data.

The first streamline strategy used by most studies is the exclusion of certain life cycle phases. Thus, most studies do not cover a complete cradle-to-grave perspective. The use and disposal stage is excluded by the cradle-to-gate assessments; gate-to-grave assessments exclude the environmental impact of certain inputs. However, as most studies do not treat all inputs or products in the same way, a subdivision (cradle/cradle* and grave/grave*) was made in Table 1. Studies with a 'cradle' perspective include the environmental impact of certain inputs, such as fertilizers, but exclude the environmental impact of other inputs, such as construction materials. Therefore, a 'cradle*' perspective is only assigned to studies that include the environmental impact of all inputs. A 'grave*' perspective includes the disposal and use phase of all coproducts, where a 'grave' perspective only includes the main product. The disposal of waste should also be considered within the system boundaries. However, the waste streams are often not taken into account, or a recycling efficiency of 100 percent is assumed. A good example of a cradle*-to-grave* system boundary can be found in the study by Stephenson et al. [30]. Some studies use criteria to exclude processes which are considered less relevant (e.g., [42]). However, the relevant inputs and processes can only be determined if their environmental impact has already been assessed [113–115]. For example, the often-neglected infrastructure emissions can be a significant contribution to the overall environmental impact [116]. Hence, this first streamline strategy is not valid, as important contributions to the overall environmental impact will be neglected by the exclusion of certain life cycle phases [115].

The second streamline strategy is the reduction of the environmental impacts included in the assessment. The study by Resurreccion et al. [29] used this streamline strategy and referred to their study as a 'partial LCA.' Due to the low TRL level of algal-based biorefineries, at this point it is not clear how the environment will be affected and which environmental impact categories will be relevant. Consequently, the choice of impact categories varied widely over the reviewed studies. Although most studies were limited to one or two impact categories, some authors, such as Collet et al. [32], for instance, included a broader range. Climate impacts and resource depletion were frequently used impact categories. Resource depletion can include a wide range of resources, such as minerals, fossil fuels, water, soil, and biotic resources. Most of the reviewed studies consider fossil fuels and water consumption; however, some studies based on energy use do not make the specifications towards fossil fuels. Other impact categories, which were considered less frequently, were eutrophication, acidification, ecotoxicity, human toxicity, photochemical smog, ozone depletion, ionizing radiation and air emissions. Although only a few studies included these impact categories, the impact of algal-based biorefineries in these categories could be substantial [33]. Therefore, the exclusion of relevant environmental impacts can lead to incorrect or irrelevant conclusions [110].

The third streamlining methodology to cope with the low TRL was the use of surrogate data. Surrogate data originates from a similar process where more accurate data is readily available. An example is the use of the soy transesterification process as a proxy for the transesterification of algal biomass [39,65]. According to Graedel [115], who conducted a survey among multiple LCA practitioners, this streamline methodology is the only valid methodology included.

Although an environmental assessment methodology can be streamlined to adapt to earlier TRL stages, this streamlining should not be interpreted as the exclusion of relevant life cycle phases or impact categories. For that reason, the TRL mismatch between the technology and the methodology leads to streamline methodologies which alter the system boundaries of the assessment and the impacts considered.

The economic studies assess an algal-based biorefinery on a hypothetical commercial scale. A large amount of data is needed to incorporate all relevant economic costs and revenues. However, this large amount of data is currently not available for algal-based biorefineries. Therefore, some economic assessments adapt their goal to only calculate the costs or revenues of the project. Another approach is to exclude some costs or revenues like infrastructure, waste disposal and indirect costs (for example, labor, overhead). A third approach to cope with the low data availability is the use of cost data from the literature or proxy data [93]. Literature data corresponds to a specific year; as prices and costs are not constant over the years, this time setting needs to be incorporated. Most studies make use of inflation rates or specific price indices (such as CEPCI). However, some studies ignore this time problem. Literature data also corresponds to a specific capacity or scale. Sizing factors ($n$) are used by some studies to scale the equipment and infrastructure cost relative to their capacity [80,106]. However, most economic studies do not incorporate economies of scale and use a linear sizing factor.

### *3.3. Methodological discrepancies*

The third reason is related to varying methodological choices. For environmental assessments, these choices concern the approach of the LCA, the functional unit, impact allocation and temporal and spatial scale. There are two broad strategies to approach an LCA: an attributional or a consequential approach. An attributional approach focuses on the evaluation of the direct environmental flows which can be attributed to the process [117]. The main objective of an attributional LCA will be the assessment of a product. The consequential approach takes the consequences, both direct and indirect, of the process on the entire environmental system into account [118]. However, the assessment of these consequences induces a high level of uncertainty in the model, as it is dependent on underlying economic prediction models. An example of such a consequential impact is the assessment of the Land Use Change [117]. Therefore, the consequential LCA is more appropriate for policy decisions [17]. As both approaches have a different objective and consequently will follow different strategies, the identification of the followed strategy is important. However, the LCA approach was only mentioned in the study by Grierson et al. [33] and in the study by Resurreccion et al. [29].

The functional unit enables a comparison of the environmental impacts over different products or processes [110,119]. As an LCA aims at the environmental assessment of a product, most studies use a product-based functional unit. This functional unit can be expressed in terms of mass, energy content, volume or functionality of the end product. An energy-based functional unit can also be considered as functionality-based. If the energy content is used, both the lower heating value and the higher heating value have been used by the studies. Some studies use a time-based functional unit, where the environmental impact of a project is averaged over a certain period of time. Therefore, a time-based functional unit is based on the project instead of on the product. As it is not clear which functional unit is the most appropriate, the choice for a specific functional unit is entirely based on the author's perspectives.

By definition, an algal-based biorefinery is comprised of multiple end-products. Therefore, the environmental impact should not be allocated to one end-product, but divided over the different end-products. The ISO guidelines provide three hierarchical allocation approaches [109,120]: subdivision, substitution and partitioning. (1) Subdivision divides the overall process in monofunctional single-operation unit processes. This way, allocation can be avoided. However, from an algal-based biorefinery perspective, the subdivision into single processes is not possible. (2) Substitution replaces the coproducts with similar products from other production processes. This method is also known as the displacement or system expansion method. It can be used as an application of a consequential LCA, as it is not limited to the main direct effects of the process or products, but includes the substitution of conventional technologies [118]. However, the identification and quantification of these conventional technologies can be a major challenge for this allocation method [121]. (3) Partitioning allocates the impacts over the products based on an allocation criterion. This allocation criterion is usually based on mass, energy content, functionality or price of the products [121]. The Renewable Energy Directive (RED) advises to use the energy content as an allocation criterion [122]. However, allocation based on energy content is only valuable when the algal-based biorefinery solely consists of energy products. The exergy content also includes flows of matter, and has for that reason been suggested as an alternative partitioning criteria [123]. Cherubini et al. [124] suggested a hybrid allocation measure combining both substitution and partitioning. This method was tested and further elaborated by Sandin et al. [125]. However, a hybrid method is less transparent and objective compared to pure partitioning. The reviewed studies used both substitution and partitioning. Different allocation criteria were used for the partitioning. Similar to the choice of a functional unit, the choice of an allocation methodology can have a large influence on the results [124–126].

As stated by McKone et al. [127], the temporal and spatial scale can be of major influence. The effects of the temporal scale were included in the environmental assessment studies in three different ways: (1) the definition of a time horizon for the Global Warming Potential (GWP) indicator, (2) the definition of a lifetime for the facility and/or equipment, and (3) the definition of a time horizon for the entire project. The second approach was mostly used to incorporate the environmental impacts from the infrastructure. The spatial scale has a large influence on technological parameters, like the biomass productivity; moreover, it is also an important consideration when waste materials such as wastewater or flue gas are included as an input to the process. Most studies only defined the country of their hypothetical production plant, as this defines the electricity composition used for the energy supply. However, a few studies (e.g., Vasudevan et al. [51]) did include detailed assessments of appropriate locations [51,65].

For economic assessments, the methodological choices are related to the definition of the life span, depreciation period, discount rate, functional unit and spatial scale. Due to the annual variation of costs, revenues and profits, the economic profitability of an algal-based biorefinery needs to be defined over the entire life span of the project. The definition of this life span varied over the different studies. The depreciation period of certain equipment defines the period until this equipment loses its value. However, most studies use one depreciation period for all sorts of equipment, and the length of this depreciation period also varied. To incorporate the opportunity cost of money, future costs or revenues can be discounted. However, the used discount rate also varied among the studies. Resurreccion et al. [29] included three different assumptions for this discount rate to assess its impact on the overall profitability of the project.

The functional unit, in accordance with the environmental assessments, defines on which level the economic profitability is displayed. Most studies that calculate investment criteria use the entire project as a functional unit. However, some of these studies specify the economic profitability per ton, gallon or MJ biodiesel. The studies, which only calculate the costs or revenues, have a larger variety in functional units.

In accordance with the environmental impact, the specific location of the algal-based biorefinery can also have a large impact on the profitability of the project. Both technological parameters (for example, biomass productivity) and economic parameters (for example, specific taxes or rent costs) are dependent on the location. Some studies, like the study by Davis et al. [103], include a detailed resource assessment to specify a suitable location for the algal-based biorefinery. Other studies define the specific location for their production plant on a country or regional level, or exclude the definition of a spatial scale.

### *3.4. Integration of different dimensions*

#### *3.4.1. Integration of the technological process*

The economic profitability or environmental impact of an algal-based biorefinery depends on the specific technological process underlying it. Most studies include a technological assessment to define this process and calculate the input and output flows. However, some studies do not include this technological assessment and are restricted to an environmental or economic assessment. Studies defined as combined in this review do include a technological assessment; however, they do not completely integrate this technological assessment. An integrated technological and economic/environmental assessment performs one assessment where the technological parameters are directly linked to the environmental/economic output parameters. Such an integrated approach allows for safeguarding environmental and economic feasibility during the maturation of the technology. The integration of the environmental and economic assessment into one assessment has also been recommended by different studies [18,24]. The adaptation of certain technological parameters may highly improve economic profits. However, this same adaptation can be disastrous for the environmental impact. An approach that integrates all three dimensions will directly translate the effect of an improved technological parameter on the environmental and economic feasibility during each TRL stage.

An important asset of an integrated approach is the possibility to assess the sensitivity and uncertainty of all input parameters for all technological, economic and environmental output parameters. Two different types of sensitivity analyses are defined in this review: (1) a local sensitivity analysis and (2) a global sensitivity analysis. A local sensitivity analysis is limited to the inclusion of a few alternative values for the assumed key parameters, while a global analysis includes a continuous range of variation over all input parameters. Such a global sensitivity analysis is only feasible when a dynamic connection exists between the different dimensions.

Of the 64 environmental assessments, 42 performed an integrated technological and environmental assessment. The environmental impact parameters were directly linked to the technological process. Most environmental impact categories in this review are normalized to a certain technological input or output flow (for example, $m^3$ water consumption, kg $CO_2$-equivalents, kg

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CFC-11 equivalents, and kg $SO_2$-equivalents). Therefore, these impacts can be directly calculated in the technological assessment. If more environmental impacts are included, or if the environmental impacts are weighted and aggregated to certain indicators, the focus shifts more towards the environmental part of the assessment. Eighteen of the environmental studies were classified as combined technological and environmental assessments. A detailed technological assessment was often included. The output from this technological part was then used as static input data in the environmental assessment. The dynamic linkage between both dimensions was missing.

Nineteen economic studies specifically aimed at performing a techno-economic assessment (TEA). However, seven of these studies only combined the technological and economic assessments, as they did not display a clear dynamic connection between the technological and economic assessments. Therefore, they were not classified as integrated technological and economic assessments. Some of these TEAs did not include a full economic assessment, being limited to a cost assessment. Only two studies specified what a TEA meant and what it should include. According to Coleman et al. [98], a TEA aims at "identifying and understanding key costs and subsequent technology constraints that potentially affect the commercialization and success" and enables a "measure of performance relative to cost among various technologies and design scenarios." Although these definitions mention the link between the technological and economic dimensions, the integrated aspect is not emphasized, as they are limited to specific scenarios. Moreover, as only the costs are considered, a complete economic assessment is not performed. According to Davis et al. [103], a TEA is "an engineering costing method that determines selling prices to evaluate and quantify economic implications for technology options". They also referred to a methodology developed by Aden and Foust [128], which focuses on an integrated assessment by means of a process flow diagram and mass and energy balance. The economic viability is assessed with a cash flow analysis based on the specifics of the process. A sensitivity analysis is included to enable the assessment of the effect of varying parameters on the economic output parameters. As this methodology does integrate the technological and economic assessments, it can be considered a valid integrated technological and economic assessment.

Van Dael et al. [129] created a framework methodology for the execution of a TEA that extended this definition, adding a market study as the first step for their framework methodology. The market study provides information concerning the competitors, customers, market sizes, expected costs and revenues, and market trends. Therefore, it is an important aspect of the economic part of the techno-economic assessment. None of the studies classified as an integrated technological and economic assessment in this review included a market study.

### 3.4.2. *Integration of environmental and economic assessments*

Sustainability is based on the integration of the three different dimensions. Most of the assessments only covered one dimension of sustainability. However, some studies did include both environmental and economic assessments. These studies are displayed in Table 3. Most of these studies combined two separate assessments, performed in a sequential order. By separating the two assessments, the connections between the two dimensions get lost. An integrated assessment would be able to use common system boundaries and assumptions to arrive at a general conclusion over the sustainability of algal-based biorefineries. If the ISO guidelines had been followed, such framework could have been provided by the two studies which aimed at LCA-LCC studies.

Kovacevic and Wesseler [79] determined a total cost by internalizing both the external environmental and social costs. Therefore, this study could be considered an integrated economic-environmental assessment. However, the technological dimension was not integrated.

**Table 3**
Overview of combined assessment literature on microalgae-based biorefineries.

| | Ref[b] | FU[c] | | Imp[d] | | SA[e] | | Int[f] | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | Env | Ec | Env | Ec | Env | Ec | T-En | T-Ec | En-Ec |
| Opt[a] | | | | | | | | | | |
| X | [82] | V | V | CC | Pr | G | | Int | Int | Int |
| X | [80] | T | T | CC | Pr | | L | Int | Int | Int |
| X | [72] | M | T,V | CC | Pr | | | Int | Int | Int |
| X | [40] | F | F | CC,En,Eu,OI | Pr | L | L | Int | Int | Int |
| X | [45] | V | P | CC | IC | L | L | Int | Int | Int |
| X | [87] | V | V | En,W | Cost | L | L | Int | Comb | Comb |
| X | [86] | V | T | En,W | Pr | | | Int | Int | Comb |
| X | [85] | V | V | En,W | Pr | | L | Int | Int | Comb |
| | [62] | P | V | CC | Pr | L | L | Int | Int | Comb |
| | [29] | F | F | CC,En,W,Eu | Pr | G | G | Int | Int | Comb |
| | [60] | F | F | CC,En,W,Eu | IC | G | G | Int | Int | Comb |
| | [89] | En | T | W | Rev | L | | | | Comb |
| | [88] | T | V | En,W | Cost | | L | Int | Int | Comb |
| | [76] | En | P | CC,En | IC | L | G | Comb | Int | Comb |
| | [56] | M | T | CC,En | Pr | | | Int | Comb | Comb |
| | [78] | En$^{l}$ | M | CC,En | Cost | L | | Comb | Comb | Comb |
| | [75] | M | | CC,En,Eu,OI | Pr | L | | Comb | Comb | Comb |
| | [77] | M | T | CC,En,OI | IC | | L | Comb | Comb | Comb |
| | [81] | V | | CC | IC | G | L | | | Comb |
| | [79] | En$^{l}$ | En$^{l}$ | CC,OI | IC | | L | | | Int |

[a] **Opt** = Optimization study.
[b] **Ref** = Reference number.
[c] **FU** = Functional unit. Env: Environmental; Ec: Economic. En: Energy; M: Mass; V: Volume; F: Functionality; T: Time; P: Project; l: Lower heating value.
[d] **Imp** = Impact category. Env: Environmental; Ec: Economic. CC: Climate change; En: Energy consumption; W: Water consumption; Eu: Eutrophication; OI: Other impact categories; Pr: Profit; IC: Investment criteria; Rev: Revenue
[e] **SA** = G: Global sensitivity analysis; L: Local sensitivity analysis
[f] **Int** = Integration of technological – economic – environmental assessments. T-En: Technological and Environmental assessments; T-Ec: Technological and Economic assessments. En-Ec: Environmental and Economic assessments. Int: Integrated assessments; Comb: Combined assessments.

Optimization studies program different technological configurations to optimize technological and economic and/or environmental impacts. Therefore, they use the technological framework as a 'backbone' for their environmental and economic assessments. Although they all lacked a global sensitivity assessment, they displayed a clear dynamic connection between the different dimensions. Therefore, they were classified as integrated technological and environmental/economic assessments. In general, the optimization studies use the same boundaries for their environmental and economic assessment. Only three of these optimization studies extended their integrated methodology to a common functional unit. Five of the optimization studies used multi-objective optimization to maximize profits and minimize environmental impacts; therefore, they did not simply combine the environmental and economic assessments, but used the optimization methodology to construct a dynamic connection between these dimensions.

## 4. Environmental TEA (ETEA)

An environmental and economic assessment of an algal-based biorefinery faces four challenges, as identified in this review. Based on these four challenges, we propose a framework methodology based on the TEA framework proposed by Van Dael et al. [129], extended with an environmental assessment that is based on the LCA methodology. This ETEA is illustrated in Fig. 2 and deals with these four challenges in the following way:

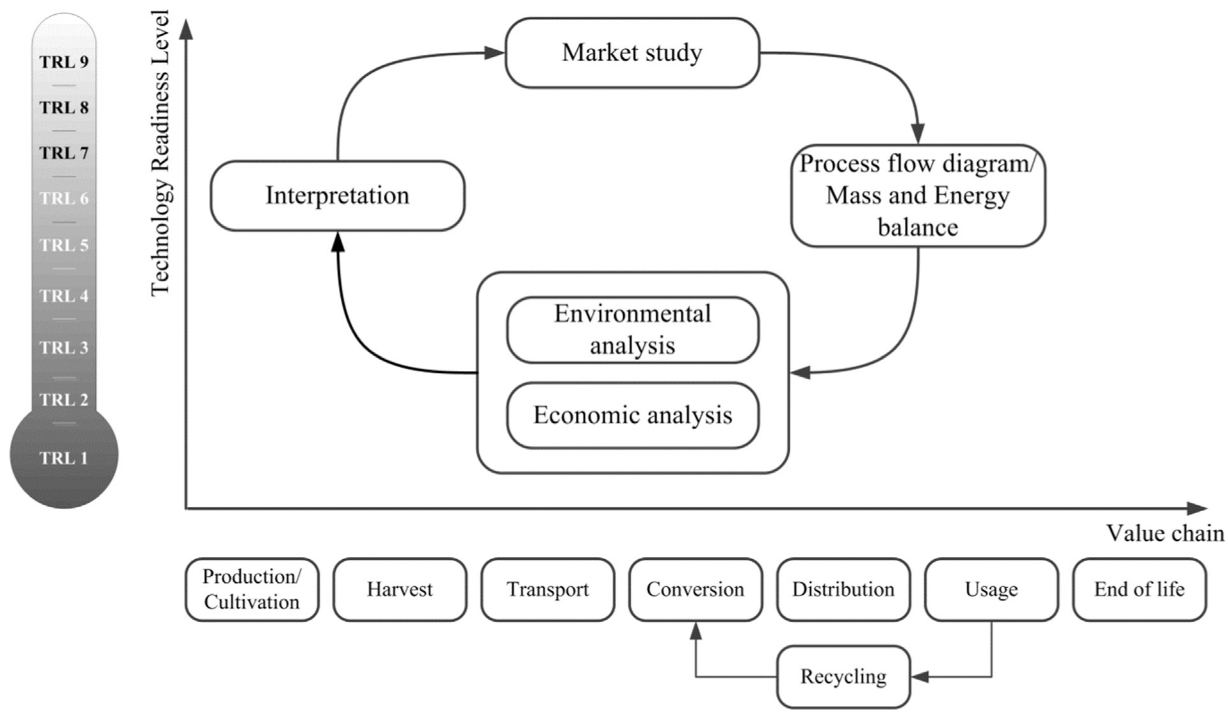


**Fig. 2.** Environmental techno-economic assessment.

A clear framework was provided. The ETEA framework consists of five clear steps, combining both the steps from the original TEA framework and the LCA framework:

(1) *Market study*. During the market study, the market perspectives – related to prices, competitive products and market trends, for example – are identified. Based on this market study, the main objectives and methodological assumptions can be identified. This step therefore combines the original market study from the TEA framework with the scope and goal definition step of LCA.
(2) *Definition of the process flow diagram and mass and energy balance*. This step links the data in the different dimensions to the process design. Although retrieved from the TEA framework, it is equal to the life cycle inventory step of LCA.
(3) *Environmental assessment***.** The environmental assessment determines all relevant environmental impacts of the project. The assessment is performed by using dynamic technological process parameters, which are obtained from the process flow diagram and from the mass and energy balances. Therefore, it is a literal translation of the life cycle impact assessment step of LCA.
(4) *Economic assessment***.** This step assesses the economic feasibility of the project based on the dynamic technological process parameters. The system boundaries are the same as those used in the environmental assessment. This step is adopted from the TEA framework. The third and fourth step could be grouped together as the impact assessment step, where the third step focusses on the environmental impact and the fourth step focusses on the economic impact assessment.
(5) *Interpretation step***.** The interpretation step facilitates the interpretation and analysis of results. A risk assessment is included to identify the probability distribution of the output parameters. This risk assessment includes a sensitivity analysis that analyzes the variation of output parameters when input parameters are varied. As the technological assessment is truly integrated, a global sensitivity analysis that varies all parameters (that is, technological, economic and environmental) is possible. This step was adopted from the LCA framework. However, the risk assessment as included in the TEA framework is a crucial analysis in this fifth step.

A main characteristic of the ETEA, which was a common property of the LCA and TEA framework as well, is the iterative approach [120,128,129]. However, none of the reviewed studies used multiple iterations for their assessments. An early iteration can consider a mere black-box model, and can make use of valid streamline technologies, such as the adoption of proxy data, to adapt the methodology to an early TRL. Later iterations can increase the level of detail for the process parameters that were identified as important. The further the technology evolves, the more detailed the assessment will be. In the market study of the first iteration, a range of relevant environmental impact categories needs to be defined. For microalgae, the studies of Efroymson and Dale [130] and Rösch and Maga [131] were performed with this objective. An early iteration should include a broad range with rough estimates of the environmental impacts. Later iterations can focus on refining the environmental impact for the important impact categories as identified by the environmental results and sensitivity analysis. Therefore, the ETEA methodology, as illustrated in Fig. 2, would allow assessing the sustainability of the entire value chain of a technology at each TRL stage.

Technological, environmental and economic assumptions should be clearly stated, when performing an ETEA. A harmonized functional unit and allocation methodology will enable a comparison of the results over different studies and a generic conclusion regarding the sustainability of algal-based biorefineries. As suggested by Collet et al. [17], the variation in results due to a different assumption should also be added to the assessment.

The manner in which the technological process was integrated in the reviewed papers was highly variable. The genuinely integrated methodologies translated the integration of the technological process by means of mass and energy balance and a detailed process flow diagram adapted to the current TRL level. This strategy was included in both the LCA framework and the TEA framework and therefore adopted in the ETEA as well. As both

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methodologies share a 'technological backbone', the ETEA therefore includes common system boundaries on process, temporal and geographical scales

## 5. Conclusions

The varying results in sustainability assessments are due to (1) the lack of a generic integrated framework, (2) a mismatch between the TRL of the technology and the assessment used, and (3) methodological differences. These three reasons are translated into three challenges related to the harmonization of assessment results covering one sustainability assessment dimension. These three challenges are extended with a fourth challenge related to the harmonization of assessments over different sustainability dimensions: (4) the integration of a common technological process, directly linked to the economic and environmental assessment.

Based on these four challenges, we suggest an integrated framework methodology, the ETEA, based on the TEA framework and extended with an environmental assessment. The iterative character of the methodology will facilitate the adaptation to different TRL stages. Clear and harmonized assumptions are crucial to enable a generic assessment of the sustainability of algal-based biorefineries. Good practices – as encountered in the different articles reviewed – should be adopted in order to avoid the different flaws found in the current sustainability assessments.

Further research can apply this proposed framework to specific algal-based biorefinery cases. The current methodology does not specify the appropriate environmental impact categories. These categories are case specific and can therefore not be defined in a generic assessment methodology. Further research is required to identify the most appropriate environmental impact categories for algal-based biorefineries. Finally, most sustainability assessments have only focused on the economic and/or environmental dimension. However, the social impact of an algal-based biorefinery should also be included in a full sustainability assessment. The integration of such an assessment methodology in the current proposed assessment framework is therefore an interesting track for further research.

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