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Sustainability Indicators for Biobased Product Manufacturing: A Systematic Review

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Abstract

Indicators are effective decision-supporting tools to assess and evaluate progress toward sustainability for a given system. This paper reviews the literature on the four pillars of sustainability (environmental, economic, technical, and social) and relevant indicators used in the agricultural, manufacturing, and materials sectors to determine a framework for manufacturing biobased products as only individual sectors have been studied in detail. The Preferred Reporting Items for Systematic Reviews and Meta-analyses (PRISMA) methodology is used to select 40 papers for review in this study. This paper suggests 22 categories encompassing 33 core measurable indicators with respective units for biobased manufacturing sectors to determine the sustainability of an end product while holistically understanding the standpoint of biomaterial industries in assessing a sustainable supply chain.

Keywords: sustainability, indicators, biobased, manufacturing, production, industry

1. Introduction

Within the past decade, manufacturers have dramatically increased efforts to develop plant-based, renewable, and recyclable materials. Ford Motor Company's development of foams, plastics, and composites from plant-based fibers (Ford Motor Company, 2017); DuPont's efforts to create sustainable plastics (DuPont, 2018); IKEA's dedication to using only renewable or recyclable materials (IKEA, 2017); and Coca-Cola's PlantBottle (Anderson, 2015) are a few such examples. These companies are motivated to reduce their waste, carbon footprint, and dependence on petroleum and develop materials with superior performance over conventional ones.

Although transitioning from petroleum-based to biobased materials offers potential opportunities to decrease negative environmental impacts, it does not guarantee merely positive outcomes. Poor selection of agricultural or forest resources, production systems, or harvest technologies could lead to undesirable competition with food resources, excessive chemical application, poor soil health, and high fossil fuel use in processing and transport. Manufacturers producing and using bio-derived materials are keenly interested in quantifying the sustainability of these materials to show reductions in environmental impacts and gain consumer confidence. This paper provides a compilation of science-based criteria and indicators to determine the sustainability of biobased product manufacturing. Designing product supply chains that meet sustainability goals to avoid long-term negative consequences requires quantitative indicators for decision support (Hallstedt, 2017). Herein, an indicator is defined as "a quantitative or qualitative factor or variable that provides a simple and reliable means to reflect the changes connected to an intervention" (Church & Rogers, 2006). Indicators are used to describe the effects of changes to the system of interest. The main characteristics of a good indicator are reliability (repeatable results), feasibility (availability of data), utility (results that can inform decision making), and relevance (direct relation to the question at hand) (Characteristics of Effective Indicators, 2010). A criterion is described as a second-order principle that adds meaning and operation ability to standards/principles without being a direct measure of performance. Criteria are intermediate points with which information provided by indicators can be integrated, facilitating an interpretable assessment (Fritsche et al., 2012).

Because sustainability goals can vary widely depending on the context, goal, and stakeholders, the indicators selected must contribute the most value for the purpose defined (Dale et al., 2015). For bio-derived materials, the sustainability of the biomass source, materials development, and manufacturing must all be considered. Stakeholders, objectives, and scale vary dramatically among these three areas. The perspective on sustainability varies per industry. Sustainability assessments based on standard metrics and existing methodologies can help in creating value-added products for the market that contribute to a circular economy—doing away with the concept of waste streams through a continuous loop of collection, disassembly, and reuse (Andersen, 2007; MacArthur, 2013; Pearce & Turner, 1990). Several frameworks on selecting indicators were consulted (ASTM, 2016; Dale & Beyeler, 2001; Dale et al., 2015), and a final list of categories was generated, consisting of indicators with respective units reflecting a diverse perspective for producing a biobased product.

Strategies for traditional manufacturing have focused on production processes that produce set numbers of products while increasing productivity and reducing costs and work effort. Today the manufacturing landscape is changing, and manufacturing operations and the natural environment are becoming increasingly connected (Rosen & Kishawy, 2012). Sustainable manufacturing can be seen as the interrelationships between the physical, chemical, and biological agents within industry and ecology coming into existence by the conscientious use of resources and technology to manufacture products catering to social, economic, and environmental objectives while improving quality of human life (Garetti & Taisch, 2012; Garner & Keoleian, 1995). Sustainable manufacturing, as a concept includes (1) goods manufactured by incorporating renewable energy, energy efficiency, green buildings, and other "green" and social-equity related products and (2) considering the full sustainability or total life-cycle issues related to the products manufactured (Jayal et al., 2010). Manufacturing industries have normally focused on addressing the economic aspects of sustainability. However, recently, they are addressing environmental and social sustainability issues, such as carbon footprint estimation, life-cycle management, transitioning from the traditionalist linear to a cyclical supply chain, minimizing the use of nonrenewable resources, and allowing local ecosystems to thrive by tracking the industrial metabolism (energy and material flows) to help lower impacts (Garetti & Taisch, 2012; Garner & Keoleian, 1995; Jayal et al., 2010; US Department of Commerce, 2011).

Industrial manufacturing (e.g., chemicals, synthetic polymers, solvents, lubricants) relies heavily on fossil fuels. Dwindling supplies of fossil fuels and their environmental impacts have created a demand for sustainable alternatives. Biomass-derived materials represent a promising alternative to petroleum-based products (Isikgor & Remzi Becer, 2015). In this review, biobased product manufacturing is considered using biomass as a substitute feedstock instead of producing products solely with petroleum-based resources (InnProBio, 2017). Similar to other renewable energy resources, such as wind and solar, biomass has the potential to make a positive impact on the environment, boost the economy, and reduce dependence on fossil fuels (Popp et al., 2014). Biomass differs from other renewable resources, as it is tied to farms, forests, and other ecosystems from which the feedstock is acquired (Environmental and Energy Study Institute, 2018). Its use as a substitute for nonrenewable resources can have both positive and negative environmental, economic, and social impacts (Haus, 2018). Therefore, having a non-fossil feedstock base is not sufficient for sustainability. The biomass type and where and how the biomass is produced will impact soils, water resources, biodiversity, ecosystem function, and local communities (Environmental and Energy Study Institute, 2018) and should be considered to ensure the sustainability of biomass-based products. Therefore, it is crucial to develop a set of indicators to build a framework for sustainable biobased product manufacturing.

2. Material and Method

The indicators identified in this paper are taken from a recent literature review of sustainability in three primary disciplines—manufacturing (processing operations), materials (providing required materials), and biomass (sources of agricultural feedstock and harvesting) encompassing most of the bioderived materials supply chain. There is no one-size-fits-all solution to real-world issues. Recognizing that sustainability goals, stakeholders, and inputs vary among different industries, this study identifies and categorizes each of the three disciplines' most widely accepted measurable indicators using four pillars of sustainability: social, environmental, economic, and technical, following the traditional "three-legged stool" model (as a stool cannot exist with only 2 legs) (Purvis et al, 2018), with an extra fourth pillar –technology. Currently, technology plays a vital role in determining the efficiency, energy consumption, and emissions related to a process on various levels (Dewulf & Van

Langenhove, 2005) and the reasoning behind this is included under Section 4.2 under the technical pillar indicators.

2.1 Search and Selection Procedure

Preferred Reporting Items for Systematic Reviews and Meta-analyses (PRISMA), a methodology for systematic reviews (Moher et al., 2010; Sharma et al., 2013, 2015), was used for this analysis. The databases used for the search include Google Scholar, ScienceDirect, and Web of Science. Peer-reviewed publications (research and review papers, books and conference proceedings) from 2007–2017 were reviewed. Categories (groups of indicators representing a given topic within each pillar) and indicators within each category were determined. Common units representing the indicators were first listed and grouped together to identify the more frequently used units in the reviewed articles. The resulting indicators were re-categorized based on the common units—undergoing a double filtering of sorts. In addition, information related to methods, processes, raw materials, and approach to sustainability was documented to holistically view the overarching "biomaterials" industry's standpoint with respect to assessing a sustainable supply chain. Specific search terms and inclusion and exclusion criteria for the selected papers are included in Table 1 and Figure 1.

Table 1. Keyword search terms with databases and number of papers initially selected for systematic review

Database	Keywords	Number of associated papers
Google Scholar	Biomass "sustainability indicators" (all in title)	2
Google Scholar	Biomass sustainability indicators review	3
Google Scholar	Biomass "sustainability indicators"	5
Google Scholar	Materials selection for "manufacturing" "sustainability indicators"	4
Google Scholar	Manufacturing sustainability indicators	7
ScienceDirect	Biomass sustainability indicators	5
ScienceDirect	Woody biomass sustainability indicators	4
ScienceDirect	Material selection for "manufacturing" "sustainability indicators"	13
ScienceDirect	Material selection for "manufacturing" "sustainability indicators" (all in title)	2
ScienceDirect	Manufacturing sustainability indicators	16
Web of Science	Biomass sustainability indicators from 2007–2017	8
Web of Science	Woody biomass sustainability indicators	2
Web of Science	Biomass sustainability indicators from 2007–2017 (all in title)	2
Web of Science	Manufacturing sustainability indicators from 2007–2017 (all in title)	5

2.2 Final Selection and Flowchart

Scientific literature was perused to assess and compare approaches to measuring the sustainability of manufacturing processes, biomass, and materials incorporated within various supply chains. Starting with 321,340 results from Google Scholar, 16,728 from ScienceDirect, 438 from Web of Science, and 22 additional relevant papers from other sources and searches (total: n=338,528), the title, abstract, and final review sort led to **Google Scholar, *n*=27; ScienceDirect, *n*=45; Web of Science, *n*=28;** and **additional relevant, *n*=22** papers (total: n=100 + 22 additional). The flow of the literature down-selection process is represented in Figure 1.

1) **Screening:** Duplicates and other irrelevant papers were removed. The intersection of the four pillars resulted in ***n*=82** papers being obtained.

2) **Eligibility:** The final number of full text articles taken for review was ***n*=40**, wherein papers that specifically focused on additive manufacturing, woody biomass indicators, and other specific topics were discarded as they narrowed the scope of the research topic. A few papers deemed "additional relevant" were compiled through the guidance of colleagues and mentors with expertise in these sectors, in addition to the existing methodology, for a total of **40 papers**.

3) **Inclusion:** Thus, **40 papers** were considered for final analysis.

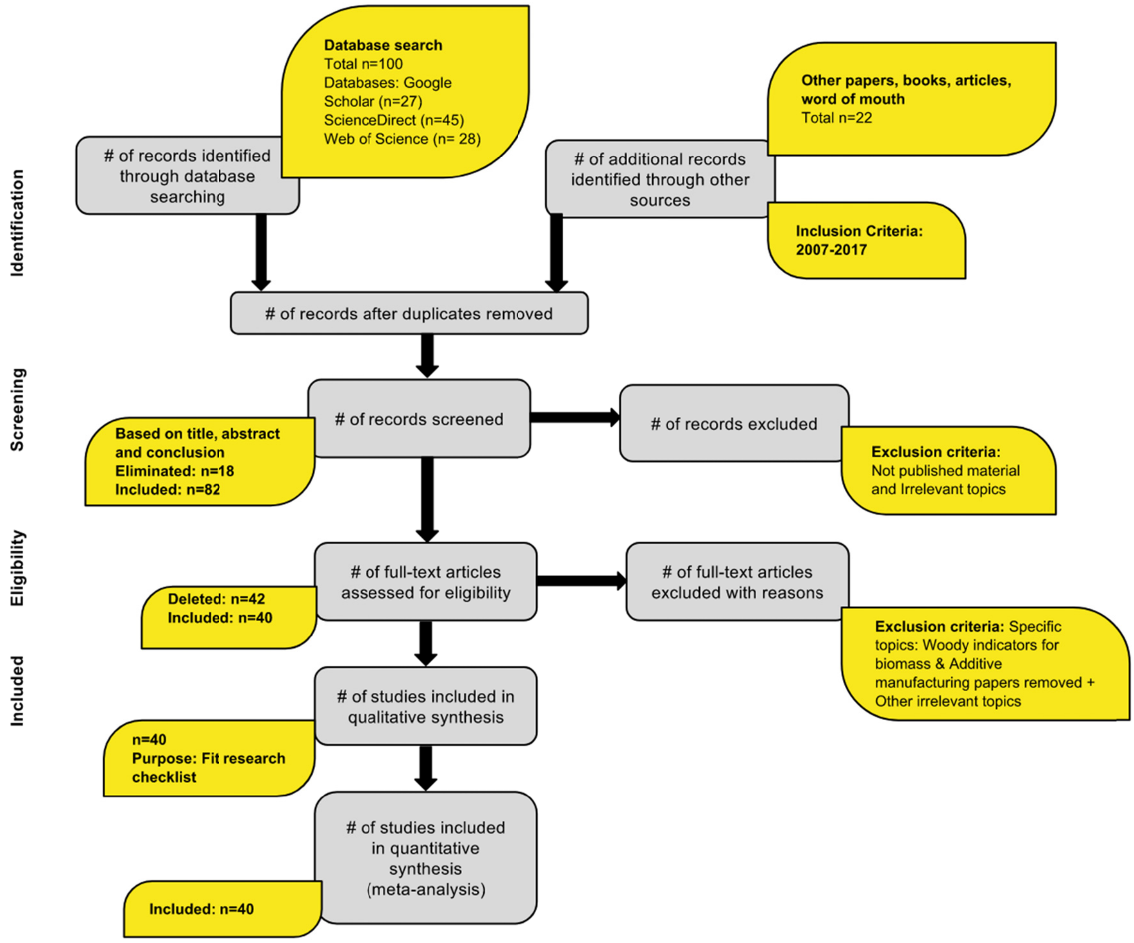

Figure 1. Systematic review plan adapted from the PRISMA methodology (Moher et al., 2009). Gray boxes represent the original suggested methodology, and yellow boxes contain additions from this study

3. Results

Indicators were kept general to represent the manufacturing, materials, and biomass industries in their entirety. Papers focusing on specific sectors such as additive manufacturing and woody biomass were removed from the list, however, such processes included within the context of manufacturing, are noted in the final set. Although there were overlaps within multiple pillars (e.g., socio-economic, techno-economic, enviro-socio-economic), they are restricted to one pillar and one category each to better understand their categorization within the three disciplines under four pillars—and to avoid double counting. A database was created in Microsoft Access so that each indicator could be thoroughly reviewed and sorted to ensure its appropriateness to the respective category, check for gaps in data, and fill them accordingly. The complete Access database used for categorization can be found at http://dx.doi.org/10.17632/krnpyx28rk.1. Results are presented under descriptive and inferential sections, followed by a detailed discussion of each category and its indicators, along with reasoning used to establish them.

3.1 Descriptive Analysis

Of the 40 papers analyzed from the manufacturing, materials, and biomass disciplines for a biobased sector, with over 1000 indicators identified, 32.5% of the indicators were related to materials science, 25% to manufacturing, and the other 42.5% to biomass (Figure 2a). The time frame for this analysis was 2007 to 2017 (Figure 2b), with no publications from 2007–2008 and merely one from 2009. Seventeen papers (the highest count for a single year) were reviewed for this study from 2017 (5 in manufacturing, 7 in materials, and 5 in biomass). The steady increase in the number of biomass-related publications from 2007 to 2017 with an interest in sustainable manufacturing and green materials could be attributed to the passing of the 'Energy Independence and Security Act' in 2007, helping gain momentum with respect to research within these sectors (EPA, 2007). Among journals from which these papers were selected, 17.5% were from *Journal of Cleaner Production*, 7.5% from *Ecological Indicators*, 5% from *Procedia Manufacturing*, and the remaining 70% from miscellaneous journals, conference papers, and books referenced in Tables SI-1, SI-2 and SI-3 within the Supplemental Information files.

(a) (b)

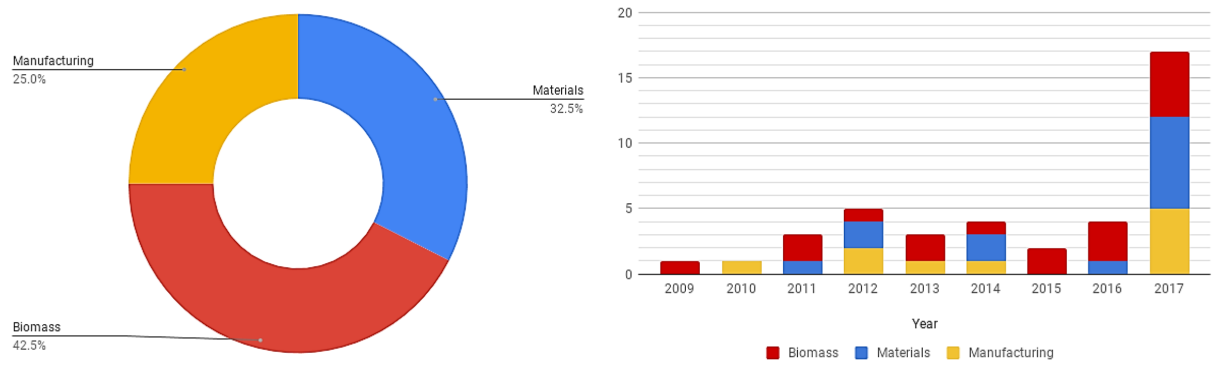

Figure 2. (a) Percentage breakdown of reviewed publications relevant to the three disciplines of materials, manufacturing, and biomass. (b) Count of publications per year from 2007 through 2017 with associated disciplines

3.2 Inferential Analysis

Manual coding was done for indicators collected through the literature to find overlaps in themes among complex sets of data (Kooduvalli, 2018). A hybrid method of combining a systematic review with meta-analysis was employed to identify categories, indicators, and their respective units for manufacturing, materials, and biomass. Tables SI-1, SI-2 and SI-3 describe various methods of incorporating sustainability, findings and case studies (if any), demonstrating the relevance of indicators within the manufacturing, materials, and biomass sectors reviewed in this study, and any other findings.

Most of the methods mentioned (1) follow a review system that pulls indicators from a variety of previously reported sources, such as Global Bioenergy Partnership, Organisation for Economic Co-operation and Development, or the United Nations Sustainable Development Goals; (2) are based on certain product requirements; or (3) use assessment methods predominant in the field of sustainability—such as LCA, multi-criteria decision models, or driving force-state-response models—or novel quantitative and qualitative methods to determine the best indicators within each sector.

4. Discussion

Considering the complexity of biobased product manufacturing, factors such as sufficiency of yield, supply and demand balance, food competition, interconnectivity of markets, and influence on other sectors (e.g., fertilizer market, food and nonfood products, farming technologies) are important for evaluation (van Dam et al., 2005). The final set of indicators were identified through a manual sorting process considering their application to the manufacturing, materials, and biomass disciplines within the environmental, social, economic, and technical pillars. Tables 2–5 summarize suggestions for categories with indicators and respective units for biobased product manufacturing. These were selected to allow quantification, ease of obtaining data, and a clear understanding of the overall impact of biobased product manufacturing supply chains. Metrics suggested by this study could be adapted to specific application areas, such as compression and injection molding, transportation, packaging, and more novel technologies similar to additive manufacturing.

4.1 Environment Pillar Indicators

For the environment pillar, ten categories were identified, focusing on environmental causes and effects that lead to changes within the immediate surroundings (i.e., air, water, land, and local ecosystems) when development ensues (Table 2).

Table 2. Environmental categories with associated indicators and units for biobased product manufacturing

Category	Indicator	Unit
Greenhouse gases (GHGs)	CO_2 equivalent emissions	CO_2 e
Waste	Allocation to landfill	Percentage of waste (%)
Air quality	Gaseous pollutants (not GHGs)	Parts per million (ppm)
	Total particulate matter (PM) (less than 10µm [PM 10] and 2.5 µm [PM 2.5]	µg/m3
Soil quality	Total nutrient content (nitrogen, extractable phosphorus, total organic carbon, sulfur, calcium, magnesium, potassium, and aluminum)	Mg/ha
	Total erosion	kg of soil lost/ha/year
Water quality and quantity	Volume of water consumed per unit product	L/product
	Concentration of nitrates, phosphorus, sediments, and herbicides/pesticides	mg/L
Energy consumption	Embodied energy per unit product	kWh or MJ/product (for electricity) [OR] BTU/product (for natural gas)
Productivity	Yield (amount of crop produced per unit area harvested)	kg of product/ha
Hazardous material	Percentage of hazardous substances	Ratio of problematic substances to total weight of the product (%)
Biodiversity	Species richness (among crops and animals)	Number of species/ha
	Infestation (pests, weeds, and parasites)	Ratio of infected number of plants or animals to total population (%)
Conservation and mitigation	Chemical/fertilizer inputs replaced	Ratio of amount of chemicals replaced to the total amount used (%)
	End-of-life channel actors	Percentage of reuse and recyclability (%)
	Cycle time	Time (s)

Greenhouse gases (GHGs), the first category under the environmental pillar, are represented by the unit *carbon dioxide equivalent (CO_2 e)*. The CO_2 e signifies “the amount of CO_2 which would have the equivalent global warming impact” (Brander & Davis, 2012). GHGs include not only CO_2 but also a variety of other gases and particles that contribute to warming the planet, such as nitrous oxide, methane, sulfur hexafluoride, perfluorocarbons, various chlorofluorocarbons, and hydrofluorocarbons (EPA, 2017a, 2017d; OECD, 2017a). For example, methane is a large contributor to climate change. It has a global warming potential of 25 years, meaning it is 25 times more potent at trapping heat than CO_2. Nitrous oxide—which comes mainly from the agriculture, transportation, and industrial sectors—has an impact 298 times greater than CO_2 (EPA, 2017d). The CO_2 e (carbon dioxide equivalent) is used as the unit to track multiple GHGs under one umbrella, considering CO_2 as baseline reference.

There are interlinkages among GHGs and other environmental categories. Secondary functions such as shipping and transportation (overhead), trade, national self-reliance (in terms of food, energy, economic development), and effects on biodiversity (e.g., as a result of land use change from natural to cultivation, shrinkage in land area resulting in loss of food availability for local organisms, increase in human–wildlife conflict) influence GHG data (Karvonen et al., 2017; Nourmohamadi Shalke et al., 2017; Smith et al., 2017; Thevathasan et al., 2014; Valdez-Vazquez et al., 2017). Manufacturing setups must consider emissions embodied within the production process, raw materials procured, and technology used (Doran et al., 2016; Heslouin et al., 2017; Rasmussen et al., 2017). For example, emissions associated with atomization, manufacturing processes such as compression molding, raw material production, casting, recycling, and transport should be considered in creating a flow model to evaluate sustainability impacts (Ashby, 2012; Priarone & Ingarao, 2017). In examining the start of any supply chain from farm, forest, or fossil fuel, the effect on the land that provides the resources plays a significant role. Some indicators in papers reviewed from the biomass discipline mentioned documenting land use change and associated GHG emissions, carbon sequestration potential, and GHG release intensity (GHG emissions released during production plus other overheads, divided by a normalization factor) (Baumert et al., 2005; Burli et al., 2016; Heslouin et al., 2017; Huang & Badurdeen, 2017; Kim et al., 2012; Mikko et al., 2013; OECD, 2017b, 2017c; Vaidya & Mayer, 2016). Accounting, sales, and marketing aspects (discussed in Section 3.6) are additional factors influencing emissions during product manufacturing (Diamantopoulou et al., 2016; Eseoglu et al., 2014; Heslouin et al., 2017). A complete list of all indicators is provided under Data Files (titled "Data and Categorization").

The **waste** category quantifies solids and effluents that are diverted to landfills. Some elements incorporated in this category are quantities of waste with traceable treatment; segregated waste; scrap metal; and other waste types such as paint and chemicals, waste sludge, wood waste, solvents, plastic, glass, consumables, and auxiliary materials (Eseoglu et al., 2014; Helleno et al., 2017; Heslouin et al., 2017; Huang & Badurdeen, 2017; Joung et al., 2013; Kim et al., 2012; Kluczek, 2017; Latif et al., 2017; Paju et al., 2010; Schöggl et al., 2017; Vinodh & Girubha, 2012; Xia et al., 2017). Once the sources and amounts of waste are known, the next step is to develop and implement waste mitigation and management strategies by adopting technologies for residue/solid waste management, treatment, storage, and disposal (onsite or offsite) mechanisms. Post-harvest losses, post-fuel production losses, residue management, and byproducts of agriculture—including nonrenewable resources from the lithosphere (fossil fuels, minerals, fossil water reserves)—must be estimated to account for all types of waste (Helleno et al., 2017; Latif et al., 2017; Maes & Van Passel, 2014; Stindt, 2017; Vaidya & Mayer, 2016; Valdez-Vazquez et al., 2017). The majority of reviewed papers point toward quantifying the amount of waste, irrespective of effluent/waste type (solid, liquid or gas). A process having multiple waste streams for the same process will need to be listed accordingly. For this reason, the indicator selected for the waste category is ***allocation to landfill*** (expressed as *percentage of waste, %*).

The **air quality** category is dominated by pollutants—gases and dust particles that do not include GHGs. Although the current focus tends to be GHGs and their effects on global warming and climate change, several toxic effluents are emitted from smokestacks that are not adequately monitored and/or whose potency is underestimated. Pollutants have large effects on health (see safety topic under Section 3.5. of the social pillar), product quality, and climate (EPA, 2017a). Businesses nowadays recognize that creating polluting supply chains does not appeal to customers (Bonini & Swartz, 2014). Catering to a simple supply and demand model will not suffice in today's markets, in which customers not only are drawn to environmentally conscious products but also expect companies to exercise stewardship (Markley & Davis, 2007; O'Rourke, 2014). Extensive studies have been conducted since the beginning of the industrial revolution to understand particulate matter (PM) and curb future emissions, which result in black lung disease and other health issues, from factories and extraction. Particle pollution can occur as dust, dirt, smoke, soot, or tiny drops of liquid (CDC, 2016). A few studies note the relationship between air pollutant release and industrial production, which enables certain elements to mobilize that were in a geochemically stable state before combustion and release (e.g., the permafrost near the poles). Studies also consider wind characteristics (e.g., intensity, speed, direction) (Heslouin et al., 2017; Maes & Van Passel, 2014). With anthropogenic changes to the atmosphere, there is a rise in levels of smog in densely populated industrial cities. Beijing and other parts of northern China to this day have record-breaking smog, which sometimes brings life to a standstill (Zhou et al., 2015). Coarser particles ranging between 10 and 25 microns cause respiratory problems such as bronchitis and emphysema; and those with diameters of 2.5 μm can become deeply rooted within the alveoli of lungs, causing irreparable damage and cancers (Ling & van Eeden, 2009). There are studies showing how these particles enter with mutagenic substances that cause damage to DNA and mutations in cells, ultimately affecting progeny (Valavanidis et al., 2008). Considering these issues, two indicators were chosen to represent air quality: ***gaseous pollutants (not GHGs)*** expressed in parts per million (ppm) and ***total particulate matter (less than 10 μm [PM10] and 2.5 μm [PM2.5]***) expressed in *$\mu g/m^3$* (Eseoglu et al., 2014; Gaitan-Cremaschi et al., 2015; Helleno et al., 2017; Heslouin et al., 2017; Huang & Badurdeen, 2017; Joung et al., 2013; Karvonen et al., 2017; Kim et al., 2012; Kluczek, 2017; McBride et al., 2011; Nourmohamadi Shalke et al., 2017; Oliveira et al., 2013; Paju et al., 2010; Schöggl et al., 2017; Thevathasan et al., 2014; Vaidya & Mayer, 2016; Xia et al., 2017).

Soil quality characteristics are defined by two main factors throughout the papers reviewed—nutrient content and rate of depletion by erosion. The terms "minerals" and "nutrients" can be used interchangeably within the context of soil quality. Minerals are inorganic elements that become nutrients when required by plants. They are classified as macronutrients (carbon, hydrogen, oxygen, nitrogen, phosphorus, sulfur, potassium, calcium, magnesium, sodium, and silicon) and micronutrients (iron, manganese, copper, zinc, molybdenum, boron, chlorine, and nickel) based on the concentrations within plant tissues required for survival (Mengel et al., 2001). However, excess nutrients can have adverse effects, such as eutrophication resulting in uncontrolled algal blooms, cutting off oxygen supply for many local plants and animals and destroying certain ecosystems. This problem is aggravated by industries dumping nutrient-rich effluents into water bodies without proper treatment. On the agricultural front, fertilizers and other leachate from fields enter groundwater, causing pollution and harming locally available potable water (EPA, 2017b, 2017c). In the reviewed papers, several mentioned quantifying nutrient content (Diamantopoulou et al., 2016; McBride et al., 2011; Oliveira et al., 2013; Thevathasan et al., 2014). They also looked into other soil health issues, including standing tree biomass; soil organic carbon; pH; dehydrogenase activity (the total range of oxidative activity of soil microflora) (Järvan et al., 2014; Wolińska & Stępniewska, 2012), expressed in units of µg TTC/g h, based on the triphenyltetrazolium chloride method (Lin et al., 2017); fluorescein diacetate (FDA) hydrolysis (µg FDA/g h), a measure of enzyme activity; and bulk density (g/cm^3) (Burli et al., 2016; Diamantopoulou et al., 2016; Diaz-Balteiro et al., 2017; Fortună et al., 2012; Gaitan-Cremaschi et al., 2015; Haverkort et al., 2009; Kudoh et al., 2015; McBride et al., 2011; Oliveira et al., 2013; Rasmussen et al., 2017; Smith et al., 2017; Vaidya & Mayer, 2016). The papers also track soil balance to estimate total nutrients as import minus export, nitrogen mineralization, and rate and estimation of carbon release and sequestration (CO_2-C/g) (Oliveira et al., 2013; Rasmussen et al., 2017; Smith et al., 2017). Sequestration looks at the potential for biomass to absorb and store carbon from the environment, acting as a sink for the pollution created by burning fossil fuels. Therefore, one of the indicators selected for soil quality for biobased materials was ***total nutrient content*** (expressed in *Mg/ha*). It can be applied to several nutrients: nitrogen, extractable phosphorus, sulfur, calcium, magnesium, potassium, aluminum, and total organic carbon. The second key factor in soil quality is the amount of soil lost as a result of natural or anthropogenic activities. Erosion is known to cause severe problems in agriculture, especially in regions of high wind or rainfall, leading to loss of fertile topsoil (humus). Severe erosion can result in flooding due to poor porosity—a reduced capacity to retain water—and drought (Sheppard, 2017; WWF, 2017). Therefore, the second indicator identified was ***total erosion*** (expressed as *amount of soil lost per hectare per year*) (Haverkort et al., 2009; Oliveira et al., 2013; Rasmussen et al., 2017; Smith et al., 2017; Thevathasan et al., 2014; Valdez-Vazquez et al., 2017), which involves quantifying and combating the problem of erosion in agricultural fields.

The **water quality and quantity** category consisted of indicators measuring nutrients and pollution in water, in addition to those used for certain processes in industries. Factors contributing to nutritional loading of a water body include flow rates, crop water productivity, areas of use, and associated hydrological processes. In addition, nutrients added from chemical inputs and industrial effluents that leach into water bodies (both lotic and lentic systems) may severely affect local flora and fauna (Fortună et al., 2012; Kim et al., 2012; McBride et al., 2011; Rasmussen et al., 2017). Quantitative measurements determine whether a given nutrient is above or below a certain permissible limit, measuring pH, chemical and biological oxygen demand, and suspended sediment concentration. Qualitative measurements help determine the presence or absence of these nutrients, as well as other visible characteristics such as color and turbidity (Gaitan-Cremaschi et al., 2015; Karvonen et al., 2017; McBride et al., 2011; Paju et al., 2010; Thevathasan et al., 2014; Vaidya & Mayer, 2016). Water for quantitative analysis must be sampled only following proper guidelines for location, frequency, storage, and methodology (WHO, 2017). Measuring the amount of withdrawal due to evapotranspiration (yield/mm), uptake by crops, and consumption for irrigation and miscellaneous activities (mm of irrigated water) allows companies to understand baseline water requirements for crop production and introduce water-saving mechanisms such as rainwater harvesting for onsite use or groundwater recharging to help local aquifer systems. Quantifying water usage at each stage help in developing strategies for conservation and mitigates adverse environmental impacts in the future. Water footprinting, for example, assesses the amount of water embedded within the life cycle of a product from cradle to grave. It resembles an LCA (an assessment characterizing and quantifying all inputs and outputs of a product life cycle "from birth to death") and highlights hotspots of greater environmental concern to aid in planning alternatives (EPA, 2006; Klöpffer, 1997; Sustainable Facilities Tool). Discussions revolving around the water-energy-food nexus are becoming increasingly important because all three of those resources are rapidly becoming scarcer (FAO, 2017). The indicator chosen for water quantity is ***volume of water consumed per unit of product*** (expressed in *L/product*) and the indicator for water quality is ***concentration of nitrates,***

phosphorus, sediments, and herbicides (including pesticides/fertilizer/other chemical inputs) (expressed in *mg/L*).

Energy consumption is a critical category having significant impacts on cost. Important characteristics of energy such as fossil fuel consumption, electricity, heat, power, casting, and other specific process-related energy calculations have been reviewed and can be accessed within the Data File titled "Data and Categorization" for further reference. Today, organizations are interested not only in producing energy onsite but also in evaluating the energy embedded within the entire supply chain. It is important to track various types of energy used (in the form of electricity, natural gas, fuel, and others) during processing, distribution, transportation. and use—as well as end-of-life channels, including recycling streams—along with sources and regional energy mixes of renewable and non-renewable sources (Ashby, 2012; Diamantopoulou et al., 2016; Eseoglu et al., 2014; Fortună et al., 2012; Gaitan-Cremaschi et al., 2015; Helleno et al., 2017; Heslouin et al., 2017; Huang & Badurdeen, 2017; Kim et al., 2012; Kluczek, 2017; Latif et al., 2017; Maes & Van Passel, 2014; Paju et al., 2010; Priarone & Ingarao, 2017; Smith et al., 2017; Stindt, 2017; Vaidya & Mayer, 2016; Valdez-Vazquez et al., 2017; Xia et al., 2017). This concept, called "embodied energy" (EE), considers all components and processes embedded within the supply chain to represent one aspect of its environmental impact in relation to the amount of energy consumed (which includes source energy) (Embodied Energy; ISO 14040, 2006; Material Use: Embodied Energy, 2014). EE can be estimated using a number of methodologies. For example, LCA software such as SimaPro and GaBi can assess this, using the embedded Cumulative Energy Demand (CED) method (another single-issue methodology within the LCA framework) (Gürzenich et al., 1999; What Is SimaPro?). The ICE database developed by Circular Ecology provides EE values for building materials. Similarly, the Fiber Reinforced Polymer Composite Energy Estimator developed by Oak Ridge National Laboratory provides a database of thermoplastics and thermoset materials and associated manufacturing processes to aid EE calculations for alternative and novel manufacturing processes (Das & Armstrong, 2017; Embodied Energy and Carbon—The ICE Database). Some common indicators found under the energy consumption category are energy consumption with respect to products and processes, renewable energy sources, transportation, energy efficiency of the product, intensity (MJ/ha), energy from forest-based biomass compared with fossil fuels (economic viability), and net energy import dependency. ***EE per unit of product*** (expressed in *kWh* or in *MJ/product* or *BTU/product*) is one of the commonly cited indicators within the energy consumption category and has been chosen to represent the energy category. It is closely related to energy intensity and efficiency (i.e., the amount of activity or product that can be produced with a given amount of energy) (EERE, 2017a, 2017b). The definition of energy efficiency relating to this context can be found from the US Energy Information Administration: "using technology that requires less energy to perform the same function" (EIA, 2017). Reviewing energy distribution profiles and consumption percentages offers the potential to estimate and increase energy efficiency at every step and decrease consumption.

Productivity is commonly defined as the quantity of output divided by quantity of input. This statement holds true within both the agricultural and technical spheres (Agricultural Productivity, Resources, and Related Terms, 2012; Landscape Measures: Crop Yield/Agricultural Productivity, 2007). In biobased product manufacturing supply chains, the output is the final product; and inputs include parts, materials, and labor, among others. The measures of the outputs and inputs depend on specifications such as labor productivity (output per labor-hour) and machine productivity (output per machine-hour). This category is linked not only to land, but also labor, capital, and soil properties. Specifically, influences such as land use change, area of cultivation, and soil quality (e.g., colloidal properties of humic substances and color) determine the yield of a given crop in any given year (Burli et al., 2016; Diamantopoulou et al., 2016; Fortună et al., 2012; Gaitan-Cremaschi et al., 2015; Haverkort et al., 2009; Karvonen et al., 2017; Kudoh et al., 2015; Lal et al., 2011; Rasmussen et al., 2017; Vaidya & Mayer, 2016; Valdez-Vazquez et al., 2017). For a more intricate perspective, the concept of multiple factor productivity can be considered, which looks into an array of indexes in relation to both input and output values (Council, 2012; Rehman, 2014). The output of such systems can be expressed as biomass yields, amount of fodder feedstock, or amount of materials used for an industrial process. Other related factors that could be incorporated are fertilizer and chemical input rates (kg/unit area) (Kudoh et al., 2015; Lal et al., 2011; Smith et al., 2017). The yields of biomass feedstock are influenced by factors such as slope of land, reforestation area, soil degradation, soil quality, type, variety of crop, and nutrient input. Land cover–related units that contribute to stability and resilience, patterns such as mono or intercropping systems, can also be recorded (Burli et al., 2016; Fortună et al., 2012; Oliveira et al., 2013; Rasmussen et al., 2017). Other indirect factors include landscape structure, number of vehicles entering and exiting the area, efficiency of resource use, and the capacity of the environment to meet social and ecological requirements (Gaitan-Cremaschi et al., 2015; Lal et al., 2011; Vaidya & Mayer, 2016; Vinodh & Girubha, 2012). Keeping in mind these interlinkages, it is crucial to keep indicators easy to estimate and understand. Therefore, the indicator ***yield (amount of crop per unit area harvested)*** expressed in *kg product/ha*, was identified for productivity (Burli et al., 2016; Diamantopoulou et al., 2016; Diaz-Balteiro et al., 2017; Fortună et al., 2012; Gaitan-Cremaschi et al., 2015; Haverkort et al., 2009; Karvonen et al., 2017; Kudoh et al., 2015; Lal et al., 2011; Oliveira et al., 2013; Rasmussen et al., 2017; Smith et al., 2017; Vaidya & Mayer, 2016; Valdez-Vazquez et al., 2017; Vinodh & Girubha, 2012).

Toxicity of the materials that constitute any given product largely determines its associated environmental impacts. For this reason, **hazardous material** was evaluated as a separate category to represent the amount of raw materials consumed, as industries then become responsible for their proper disposal. Raw material recyclability, degradability, toxicity, product and byproducts, durability, biodegradability, and green production rate are related to sustainability properties (Ashby, 2012; Eseoglu et al., 2014; Helleno et al., 2017; Heslouin et al., 2017; Priarone & Ingarao, 2017; Xia et al., 2017). Green production is a "business strategy that focuses on profitability through environmentally friendly operating processes." (Green Production, 2018). The main goal is to reduce emissions and effluents by making use of recycled materials, renewable energy sources and reducing life-cycle costs of products and services. Material usage is the most referenced indicator for hazardous materials among the reviewed papers; therefore, the indicator ***percentage of hazardous substances*** (expressed as *ratio of problematic substances to the total weight of the product, %*) was identified. (Canciglieri et al., 2014; Eseoglu et al., 2014; Gaitan-Cremaschi et al., 2015; Hallstedt, 2017; Helleno et al., 2017; Heslouin et al., 2017; Huang & Badurdeen, 2017; Joung et al., 2013; Kim et al., 2012; Kluczek, 2017; Maes & Van Passel, 2014; Paju et al., 2010; Stindt, 2017; Vaidya & Mayer, 2016; Vinodh & Girubha, 2012; Xia et al., 2017; Zarandi et al., 2011). This unit is recommended for entities of the biobased product manufacturing industry supply chain related to feedstock availability, processing, chemicals, and other synthetic materials used in intermediate facilities and manufacturing locations.

The **biodiversity** category analyzed indicators studying impacts on flora and fauna, wildlife preservation, and natural events affecting growth. Specific measures related to biodiversity were studied, such as growth rate, indicator species, endangered habitat zones, pollination rate, stocking rate (number of animals/hectare), biodiversity-related intervention with the use of herbicides and pesticides (also with respect to monoculture versus agrosystems). Other issues—including soil biota index; biodiversity index; and diversity of genes, species, and ecosystems—also were studied (Diamantopoulou et al., 2016; Gaitan-Cremaschi et al., 2015; Helleno et al., 2017; Karvonen et al., 2017; McBride et al., 2011; Oliveira et al., 2013; Smith et al., 2017; Stindt, 2017; Thevathasan et al., 2014; Vaidya & Mayer, 2016; Xia et al., 2017). Considering these factors, the indicator ***species richness (among crops and animals)*** was chosen to represent biodiversity, measured in *number of species/unit of area*. Pressures from pest infestations also cause damage. Hence, farmer-reported pest pressure and weed infestation scores were considered, as well as the number of pest species suppressed and crops damaged. Natural disasters were noted separately by considering plant resilience through relative losses due to disaster. Abiotic stresses due to manmade changes are other possibilities, relating to ecosystem damage due to waste absorption or emission capture and storage which affect food and shelter availability within certain habitats and reserves (Burli et al., 2016; Smith et al., 2017; Vaidya & Mayer, 2016; Valdez-Vazquez et al., 2017). For this reason, ***infestation (with respect to pests, weeds and parasites)*** was identified as a second indicator (expressed as *ratio of number of infected plants or animals to total population, %*). Timely conservation efforts are extremely important to rectify damage caused by pests by monitoring trends in local biodiversity, tracking endangered animals (IUCN Red List Index) within various taxonomic groups (IUCN, 2017), tracking the number of days where biomass harvesting coincides with critical wildlife breeding seasons, and lowering the risk of forest fires. In relation to materials and manufacturing, the question to be addressed is whether production would lead to biodiversity loss —if so, in what ways—and whether there are methods to avoid these processes partially or entirely, in addition to mitigation efforts. Damage prevention and preservation of all life forms affecting the industrial chain starts with the sources of raw material and extends to end-of-life, including recovery and recycling efforts (Ashby, 2012; Burli et al., 2016; Diaz-Balteiro et al., 2017; Joung et al., 2013; Lal et al., 2011; Maes & Van Passel, 2014; Oliveira et al., 2013; Rasmussen et al., 2017; Smith et al., 2017; Valdez-Vazquez et al., 2017).

The **conservation and mitigation** category specifically looks at unique perspectives relating to water, energy, emissions, alternative technologies, and consumption. In light of the ever-increasing scarcity of freshwater in many parts of the world, it is critical to find innovative ways to reduce the amounts used for industrial and agricultural applications. As with any other issue, water scarcity needs to be addressed after understanding consumption—measured through availability and reuse and expressed as freshwater consumption per unit of generated energy (m^3/MJ). Energy measurements are covered extensively under the energy category, in terms of assessing the EE of a system (MJ/kg) and analyzing the influence of transportation on energy and emissions. Sharing private cars by carpooling and use of renewables-based energy help mitigate carbon emissions. Carbon footprint measurements conducted through GHG audits are useful for calculating effects on climate change. Other factors also should be considered, such as decrease in CO_2 due to workforce contributions based on decision making (e.g., reducing CO_2 emissions or energy use via sustainable behaviors during a period), energy efficiency schemes, and implementation of waste management strategies (Burli et al., 2016; Heslouin et al., 2017; Kim et al., 2012; Latif et al., 2017; Stindt, 2017; Valdez-Vazquez et al., 2017). With regard to extraction of materials from the earth, dependency on fossil fuels and other ores used in industry are causing havoc not only for wildlife but also for human settlements and health (USC, 2016). The amount of petroleum extracted per year can give us an idea about depletion of non-renewable resources, as the planet has finite resources to offer (Dale et al., 2013; Schöggl et al., 2017). Mitigation efforts in terms of farming include replacement of chemical fertilizers and inputs with organic and more natural inputs. Bearing in mind that the land is the ultimate origin of not just biobased, but all manufacturing supply chains in one form or another, ***chemical/fertilizer inputs replaced*** was identified as the indicator, expressed in units of *ratio of amount replaced to the total amount used, %.*

To date, people in many parts of the world use biomass to heat their homes. Energy from biomass is still harnessed as biofuels and electricity. Sacred groves and lands (common across India and parts of Africa) are places left untouched by humans because of their spiritual significance. The presence of such areas was found to influence conservation indirectly by allowing local wildlife to thrive, in turn increasing its density in those places (Gadgil & Vartak, 1976; Ruscavage-Barz, 2007). Using similar concepts, federal governments have designated "high conservation areas" to protect animals within certain regions from human interference. Alternative land management practices are considered under this indicator, focusing on substituted nutrient inputs, conservation areas, best agricultural practices for balancing nutrients in the soil, and analyses with respect to biodiversity loss (Haverkort et al., 2009; Lal et al., 2011; Rasmussen et al., 2017; Smith et al., 2017; Vaidya & Mayer, 2016). A case study from one of the reviewed papers explores six climate change scenarios with different indicators aggregated over a 100-year time period in a mountain forest in Central Spain, comparing traditional versus innovative alternative forest management systems using a customized weighting approach incorporating stakeholder preferences (Diaz-Balteiro et al., 2017). It was shown that innovative methods were superior to the traditional methods. Alternative management technologies such as those employed for pest management, storm water management, and agro-ecological processes were studied, along with end-of-life treatments with reuse capabilities, including cogeneration facilities and other efficiency-boosting engineering applications. Thus, ***end-of-life channel actors*** was chosen as the indicator, expressed as *percentage of reuse and recyclability* with regard to water, energy, and other materials. Specifically, in looking at manufacturing setups, the time for disassembly, remanufacturing techniques, and reverse logistics needs to be considered. For this purpose, the indicator ***cycle time***, expressed in the unit *time (seconds),* was also chosen (Ashby, 2012; Burli et al., 2016; Diaz-Balteiro et al., 2017; Eseoglu et al., 2014; Fortună et al., 2012; Gaitan-Cremaschi et al., 2015; Helleno et al., 2017; Heslouin et al., 2017; Huang & Badurdeen, 2017; Kim et al., 2012; Kluczek, 2017; Lal et al., 2011; Maes & Van Passel, 2014; Mikko et al., 2013; Schöggl et al., 2017; Smith et al., 2017; Stindt, 2017; Vaidya & Mayer, 2016; Valdez-Vazquez et al., 2017; Vinodh & Girubha, 2012; Xia et al., 2017; Zarandi et al., 2011).

4.2 Technical Pillar Indicators

The **Technical** pillar focuses on production, operation, and machine-related metrics (Table 3). Conversations involving technology are becoming critical as society is transformed radically through technological evolution, encompassing innovation and technology (Böhme & Stehr, 2012). This pillar was kept separate from the traditional "3-legged stool" model that focuses only on environmental, social, and economic aspects, following a pattern similar to a few recent papers that consider the same outlook. Eseoglu et al. (2014) mention efficiency as a driver for technology development by relating it to the amount of resources input for a given process. Helleno et al. (2017) integrate sustainability indicators with lean manufacturing to assess manufacturing processes. Their research is supplemented with a case study in Brazil that looks into a cosmetics and thermoplastics company with high volume and low variety of products. Mikko et al. (2013) and Kluczek (2017) also refer to technology as a fourth standing pillar of sustainability. The 21st century has seen drastic leapfrogging of various technologies (e.g., landlines to cell phones, fossil fuels to renewables, gas to electric cars); the results have affected labor as automation replaces traditional assembly line jobs, increases outsourcing of jobs overseas, and demands a more skilled workforce to displace unskilled labor (Acemoglu, 2002). Yet, positive impacts also ensue, with machines having increased efficiency that lowers energy consumption and emissions. Factors relating to tool wear rate, resource consumption within the production process, and internal material cycles play a role in production. Factors covered under operations are setup time, throughput time, finish time, and flexibility. These two aspects were combined under the category **production and operation,** and the indicator ***throughput time*** was selected, expressed as *time (s) as appropriate for biobased product manufacturing*. This indicator can be expressed in relation to biomass processing based on the crop type, processing, and manufacturing with the associated amount of product formed (Canciglieri et al., 2014; Hallstedt, 2017; Helleno et al., 2017; Kluczek, 2017; Paju et al., 2010; Schöggl et al., 2017; Xia et al., 2017).

Table 3. Technical categories with associated indicators and units for biobased product manufacturing

Category	Indicator	Unit
Production and operation	Throughput time	Time (s)
Innovation	Research with eco-design and innovation	Number of products with eco-design approach
Performance management	Quality	Number of products/batch that meets quality specifications

The thirst for knowledge and the drive to better ourselves can take the form of research and innovation. Thus **innovation** was identified as a category. Research and development funding has shifted largely from government to corporate funding in relation to application-based work. For example, the National Science Foundation has shown that, federal funding made up only 44% of the $86 billion spent on basic research in 2015. Many companies are pushing their own laboratories to come up with viable products in various fields to surpass the mounting competition and succeed commercially in the market (Mervis, 2017). Within this context, there has been a big push to create products using the concept of eco-design, which involves producing sustainable solutions as

> products, services, hybrids or system changes that minimize negative and maximize positive sustainability impacts—economic, environmental, social and ethical—throughout and beyond the life-cycle of existing products or solutions, while fulfilling acceptable societal demands/needs (Charter et al., 2001; Karlsson & Luttropp, 2006).

Similarly, according to Eseoglu et al. (2014), eco-innovation "focuses on economic growth and environmental protection for techno-social innovations." Using these definitions, it is possible to determine where and how eco-design concepts have been incorporated with respect to biobased product manufacturing. Some indicators identified are lifespan of the product, implementation of quality best practices, environmental features and components, design for manufacturing and assembly, and design aspects related to recycling and manufacturing (Eseoglu et al., 2014; Fortună et al., 2012; Gaitan-Cremaschi et al., 2015; Hallstedt, 2017; Helleno et al., 2017; Heslouin et al., 2017; Joung et al., 2013; Kluczek, 2017; Mikko et al., 2013; Schöggl et al., 2017; Vaidya & Mayer, 2016; Valdez-Vazquez et al., 2017; Vinodh & Girubha, 2012; Xia et al., 2017). The European Commission is actively promoting eco-innovation for market distribution, realizing human impact to its full extent by incorporating five points: (1) materials recycling and recycling processes, (2) sustainable building products, (3) food and drink sector, (4) water efficiency, treatment, and distribution, and (5) greening business (Eseoglu et al., 2014; European Commission, 2016). For this reason, under the innovation category, ***research with eco-design and innovation*** was chosen as the indicator, expressed in *number of products produced via eco-design*, to pinpoint exactly where such research is needed to improve subsequent assessments. Another unit that could be used is *number of patents approved per year* based on the success of new technological ideas.

The final category within this pillar is **performance management.** This itself was considered a separate pillar in some papers (Eseoglu et al., 2014; Heslouin et al., 2017; Joung et al., 2013; Mikko et al., 2013). Within this category, the topic of maintenance—related to frequency of instrument/equipment maintenance, chemicals used in the process, and associated labor cost—is discussed. Other topics are related to waste, environmental (environmental management systems), just-in-time manufacturing (operating results for both consumers and suppliers), and business-as-usual scenarios. The reviewed articles indicate that policies of a company must be open to discussion within varying levels of an organization to incorporate improvements and in turn uphold worker morale (Burli et al., 2016; Diaz-Balteiro et al., 2017; Hallstedt, 2017; Helleno et al., 2017; Huang & Badurdeen, 2017; Joung et al., 2013; Kluczek, 2017; Latif et al., 2017; Mikko et al., 2013; Nourmohamadi Shalke et al., 2017; Vinodh & Girubha, 2012). Papers related to manufacturing and operations generally echo similar perspectives and offer some indicators in regard to type of process, production technology state (machinery, tooling, material handling, work handling, machine performance data and improvement policy), production quantity per piece, technical capability, capacity of reproduction of technology used, optimization of material inputs, operational efficiency, and computer systems for planning and production (Eseoglu et al., 2014; Helleno et al., 2017; Kluczek, 2017; Nourmohamadi Shalke et al., 2017; Oliveira et al., 2013; Paju et al., 2010; Schöggl et al., 2017; Vaidya & Mayer, 2016; Vinodh & Girubha, 2012; Xia et al., 2017). Studies have looked into supply chain entities to understand diverse feedstock in relation to market acceptance and adaptability, facility requirements to meet certain methods, duration of use, time-based logistics for movement and storage of goods, supplier scheduling and delivery, reduced packaging, efficient transportation, appropriate supplier selection, and resource efficiency within production (Kluczek, 2017; Schöggl et al., 2017; Vaidya & Mayer, 2016; Vinodh & Girubha, 2012; Xia et al., 2017). The final section relates to the upkeep of all these factors—quality. With respect to industry, quality control (QC) is "a part of quality management focused on fulfilling quality requirements," and quality management consists of "coordinated activities to direct and control an organization with regard to quality" (ISO 9000, 2015). Conforming to specifications (Siemens, n.d.) to ensure quality encompasses eight dimensions: (1) performance, (2) features, (3) reliability, (4) conformance, (5) durability, (6) serviceability, (7) aesthetics, and (8) perceived quality (Garvin, 1987). Within the scope of this study, papers look at indicators that play a role in quality, such as possibility of quality fluctuations, quality loss in logistics, and possibility of quality deficits (Eseoglu et al., 2014; Helleno et al., 2017; Nourmohamadi Shalke et al., 2017; Oliveira et al., 2013; Xia et al., 2017). Within the context of biobased product manufacturing, a detailed representation of the quality of products will enable trust in such products that make it to market. Statistical QC, proposed by Walter A. Shewhart (of the US company Bell Labs) in the 1930s aided in the application of QC on a massive scale around the time of World War II. It uses statistical techniques to determine quality and uniformity among products, adding the advantage of being more reliable and less expensive. Total Quality Management is another blanket concept that stressed changing the culture and actions of an organization through management and offered improvement over traditional task performance (Naidu, 2006). Although standards vary across sectors, there are common standards for all industries that must be followed to conform to industry codes. As a result of this overarching principle, the most documentable indicator for Performance management was determined to be ***quality***, expressed in *number of products/batches that meet quality specifications reflected in the eight dimensions*.

4.3 Social Pillar Indicators

The social pillar of sustainability focuses on the human component related to industries, whether it be health and safety, feelings of well-being and job satisfaction for workers, fair trade sourcing, social justice issues, or ethical workplace behavior (Table 4). As the social pillar is yet to be thoroughly understood and quantified, the indicators and units taken from the different papers vary slightly with respect to their interpretation of categories and tend to have open-ended units as metrics for interested parties to perform such assessments. Social LCA uses indicator methodologies to quantify social impacts (midpoint and endpoint: describing the points of impact along the pathway of a system) that can affect people's working conditions locally, and to show impacts on a larger community level (Jørgensen et al., 2008).

Table 4. Social categories with associated indicators and units for biobased product manufacturing

Category	Indicator	Unit
Culture	The effect of industry on local culture	Sum of available cinemas, showrooms, theaters, museums, restaurants, universities and libraries per region (n/municipality or specific region)
Equity	Ratio of inequality	Equality of outcome/input ratios or equality relative to individual contributions
	Public opinion	Documented responses based on number of participants, hearings, employee satisfaction and stakeholders
Employee turnover	Absenteeism	Abs = NHA/NHW; NHA = number of hours absent; NHW = number of hours worked (%)
	Turnover	Tov = [(NLa+Nad)/2]/NEO; NLa = number of layoffs; Nad = number of admissions; NEO = number of employees
Health and safety	Occupational hazard	Number of new accidents per unit population
	Accident rate	ARa = NA/NEO; NA = number of accidents; NEO = number of employees
Regional development	Regional Human Development Index	HDI = (I1 + I2 + I3)/3 I1—Life Expectancy Index: Average number of years from the time of birth to death ⇨ I1 = (life expectancy in the country—25) / (85–25) I2—Education Index: Adult literacy rate (%) + Gross enrolment ratios of students in primary school through university level ⇨ I1 = (literacy rate—0) / (100–0); Ie = (enrollment in education—0) / (100–0); I2 = (2 · I1 + Ie) / 3 I3—Gross Domestic Product (GDP) index: GDP*/capita in purchasing power parity terms, based on USD ⇨ I3 = (log [*GDP per capita]—log [min. value]) / (log [max. value]—log [min. value]) *GDP is defined as the monetary value of all finished goods and services produced within a country's borders in a specific time period, usually calculated on an annual basis (Numbers mentioned in the formula are based on minimum and maximum values associated with each category. Refer to Section SI-1 under Supplemental Information for complete methodology)
Corporate social responsibility	Transparency	Percentage of indicators for which timely performance data are reported (%)
	Customer/supplier relationship	Number of customers with environmental requirements

Culture is one of the categories with the technical pillar. The Peace Corps defines "culture" as

> a system of beliefs, values, and assumptions about life that guide behavior and are shared by a group of people including customs, language, and material artifacts that are transmitted from generation to generation, rarely with explicit instructions (Peace Corps, n.d.).

It is possible to reflect on this ideology at two levels—one in relation to industrial terms and the other with respect to social ties. Incorporating local culture and people while running an industry, work and ethics issues, integration with society, access to education, and public health are some topics discussed under this category. Culture is divided into several sections that explore quantifying each of their indicators. Among the interests socially relevant to biobased industries, papers reviewed highlight recreation, corporate philanthropy, identifying corruption, protecting local/tribal heritage, and access to cultural forest products (Diaz-Balteiro et al., 2017). The impact of industry on local culture can be quantified through employment, e.g., the number of jobs that employ locals, to help understand the effect industry has on a region. For this purpose, Dale et al. (2013) mention full-time-equivalent jobs as a measurable metric to describe the number of jobs that help boost the local economy. This, in relation to how many workers are employed on farmlands, gives us a general idea of the effects of employment (Kluczek, 2017; Thevathasan et al., 2014). Workplace culture is also critical, and the attributes mostly associated with it are work ethics; loyalty; anti-competitive behavior; involvement of local organizations; relationships between local and external workers; ethical concerns such as industrial odors, noise, and traffic; and mechanisms for transparency (Eseoglu et al., 2014; Fortună et al., 2012; Lal et al., 2011; Nourmohamadi Shalke et al., 2017; Schöggl et al., 2017; Stindt, 2017; Vaidya & Mayer, 2016).

Good communication is key for a successful establishment. Indicators falling under the stakeholder cluster include support from suppliers, diversity of suppliers, responsiveness, number of complaints per product, and cooperative motivation (Huang & Badurdeen, 2017; Xia et al., 2017). Communication plays a large role in improving relations with stakeholders, facilitating a safe space for ideas and constructive criticism to be shared, and boosting morale and productivity for workers (Lal et al., 2011). Another option is to have takeback mechanisms in place and addressing benefits of a healthier community resulting from such behavior change.

Workers' active interest and ownership of the company play a large role in improving efficiency and structure. Participation in local programs, including those that consult stakeholders before making new decisions, is one way this can occur. The influence of industry on local culture explores access to information, language, and certain kinds of education for workers and their families. Some associated units count the number of participants in programs hosted by industry, number of hearings for policies and court cases, and percentage of favorable opinion.

Finally, all of these mechanisms help develop an industry culture wherein decisions relating to products' end-of-life pathways (involving the 3R's—reduce, reuse, and recycle) are key to establishing a socially sustainable facility. These include ethical treatment of organisms bred on farms and the recognition and elimination of socially undesirable products (Helleno et al., 2017; Stindt, 2017). Although there has been talk of including culture as a separate pillar of sustainability, more often than not, culture is left out except for the purpose of aesthetics in conversations relating to development, sustainability, policy, or legislation (Maraña, 2010). The relationship between culture and development was first highlighted in the publication "Our Creative Diversity," published by UNESCO in 1996 (World Commission on Culture & Development, 1995). Realizing the impact of culture on society, this was placed under the social pillar. Axelsson et al. (2013) reviewed indicators along with specific verifiers (similar to our use of units) to determine units for social and cultural categories. Mapping software such as GIS (Geographical Information System) were found to improve visualization for ethnographic studies (Axelsson et al., 2013). Fukuda-Parr (2004) talks about the importance of indicators not being statistical and descriptive, but rather evaluative. Trying to promote indicators that are measurable poses a challenge, as culture cannot be restricted to a few metrics. Considering the context of biobased industries, several perspectives were presented in 40 papers reviewed in this study. However, none of these that made the review list proposed units for cultural indicators, as they were mostly open-ended. Therefore, colleagues and indicator experts were consulted to determine appropriate indicators to enable quantification. It was concluded that **Culture** can be best represented in relation to biobased industries by calculating the indicator ***the effect of industry on local culture***, expressed in the unit *sum of available cinemas, showrooms, theaters, museums, restaurants, universities and libraries per region (n/municipality or specific region)*, where annual increases in numbers can be attributed to the growth of an industry in that area—as an influx of workers, visitors, and other businesses. Such institutions and businesses reflect local history, tradition, education, art, and culinary experience in an overarching sense (Axelsson et al., 2013; Russ & Jones, 2008).

There exists a fundamental difference between the terms 'Equality and 'Equity.' Equality refers to the identical standing of all types of people irrespective of social class, religion, economic background, language, perspectives, skills, education, and sexual orientation. However, especially within the distributive justice process, it is found that not all people begin with an equal standing in society due to varying backgrounds and systemic biases. Therefore, equity is presented as the better option. This concept can be viewed as 'relative equality,' in the sense that results show allocation based on needs rather than standing. This is coming to be an important topic of discussion within the realm of social justice. The chosen category here is **Equity,** described with indicators ***ratio of inequality*** represented by unit *equality of outcome/input ratios or equality relative to individual contributions*, and ***public opinion*** with unit *documented responses based on number of participants, hearings, employee satisfaction and stakeholders.* In economic terms, this translates to a person or group of people who are given preference in a situation to create the best outcomes to the best of their ability (Blackford, 2006; Cook & Hegtvedt, 1983). Equity has indicators that delve into topics surrounding justice, diversity, job satisfaction, connectedness, worker participation, outreach programs, and standard of living, as well as monitoring and combating negative issues related to slavery and child labor in incorporating fair trade products and practices (Burli et al., 2016; Eseoglu et al., 2014; Fortună et al., 2012; Gould et al., 2017; Hallstedt, 2017; Stindt, 2017; Valdez-Vazquez et al., 2017; Vinodh & Girubha, 2012). Within the context of job opportunity, this category looks at livable wages for workers, their rights and diversity within the workplace, and programs for women and youth. When that child labor (or any kind of forced labor) is detected, there are rules for proper economic remuneration, medical assistance, and education to deal with such violations. Rights of farmers to their land and indigenous rights are considered and protected within this category. Rights of workers with respect to freedom of speech and freedom of association, collective bargaining, and the right to strike are protected. Rules against corruption and for impartiality are established and enforced (Burli et al., 2016; Canciglieri et al., 2014; Dale et al., 2013; Eseoglu et al., 2014; Fortună et al., 2012; Gould et al., 2017; Hallstedt, 2017; Helleno et al., 2017; Joung et al., 2013; Karvonen et al., 2017; Nourmohamadi Shalke et al., 2017; Rasmussen et al., 2017; Schöggl et al., 2017; Stindt, 2017; Thevathasan et al., 2014; Valdez-Vazquez et al., 2017; Vinodh & Girubha, 2012).

A company's success can also be viewed by its rate of employee turnover. The employee turnover decision process in detail, with a descriptive flow chart, is described by Mobley (1977). Turnover rates are important from a human resources perspective as a factor in budgeting related to the number of new employees, hiring policy, and training. However, there is a significant difference between voluntary turnover (accepting other jobs, relocation, other personal reasons) and involuntary turnover (layoffs, termination, discharge); the former is preferable for a company's reputation (Mayhew, updated 2018). Generally, the process of withdrawal from the workplace begins with a rise in absenteeism (number of hours/days of absence) for a multitude of reasons besides lack of job satisfaction, such as unfavorable/unhealthy working conditions or workplace interactions, pressure from superiors, mounting job pressure, dissatisfaction with results, or several other reasons. Therefore, ***absenteeism*** is a symptom of the main issue of turnover rates, and it is considered one of the indicators to describe the **Employee turnover** category. It is expressed as a percentage with *absenteeism [Abs] = NHA/NHW, where NHA= number of hours absent; NHW=number of hours worked* (Helleno et al., 2017; Huang & Badurdeen, 2017; Karvonen et al., 2017; Kluczek, 2017; Paju et al., 2010; Stindt, 2017). It was found that companies have the potential to increase employee retention and reduce turnover rates by considering social indicators within their business framework (Helleno et al., 2017). The other indicator identified was ***turnover rate***, also expressed as a percentage (*turnover (Tov) = [(NLa+Nad)/2]/NEO; NLa=number of layoffs; Nad=number of admissions; NEO=number of employees*) (Helleno et al., 2017; Huang & Badurdeen, 2017; Stindt, 2017).

Health and safety is an integral and accountable section of any business. General safety training is mandatory in most organizations to follow OSHA standards (US Department of Labor, n.d.), even when it comes to office safety and handling. Under the category **Health and safety,** the reviewed parts were categorized under the headings of purely health, then safety, and finally a combination of both—as there was a very large overlap in several papers—to determine the most recurrent terms reflecting the category. Under health, the range of indicators included disease incidence, farmer-reported conditions related to animals and crops, occupational health/injuries and hazards, ergonomics, medical insurance coverage, and decent work (Diamantopoulou et al., 2016; Eseoglu et al., 2014; Gould et al., 2017; Helleno et al., 2017; Kim et al., 2012; Schöggl et al., 2017; Smith et al., 2017; Valdez-Vazquez et al., 2017; Xia et al., 2017). Because the environment within any facility plays a large role in determining the effect on human health (which can be expressed as DALY—disability-adjusted life years), the indicator ***occupational hazard*** was chosen, expressed as *number of new accidents per unit of population* to extrapolate other information related to frequency of incidents and types of accidents. Safety aspects covering noise levels and other disturbances, accident-related absences, exposure to a high-risk work environment, and accident rates top this list (Dale et al., 2013; Doran et al., 2016; Eseoglu et al., 2014; Helleno et al., 2017; Heslouin et al., 2017; Huang & Badurdeen, 2017; Karvonen et al., 2017; Kim et al., 2012; Mikko et al., 2013; Schöggl et al., 2017; Stindt, 2017; Vinodh & Girubha, 2012). ***Accident rate (ARa) where ARa = NA/NEO; NA=number of accidents; NEO=number of employees*** was chosen as the indicator for safety as it includes other associated protocols in question. (Helleno et al., 2017). Health and safety topics also cover risk to community, public health and sanitation, cleanliness of operations, and maintenance, along with labor practices (Eseoglu et al., 2014; Helleno et al., 2017; Huang & Badurdeen, 2017; Kim et al., 2012; Kluczek, 2017; Latif et al., 2017; Nourmohamadi Shalke et al., 2017; Stindt, 2017; Xia et al., 2017).

Regional development is seen as a result of industries having a positive influence on the local economy and its people. This influence could be due to several reasons:

On the community front—Infrastructure projects connecting manufacturers to suppliers and clients provide local infrastructure such as roads, bridges, and railway lines. Indirectly, this development boosts the service industry related to schools, universities, banks, information and communications technology companies, and hospitals (Fortună et al., 2012; Kluczek, 2017; Lal et al., 2011; Vaidya & Mayer, 2016). Access to modern technology, health care, waste services, energy, education, social capital formation, and integration of new technologies are influences an industry can have over a region (Eseoglu et al., 2014; Fortună et al., 2012; Gould et al., 2017; Kudoh et al., 2015; Rasmussen et al., 2017; Vaidya & Mayer, 2016; Vinodh & Girubha, 2012; Xia et al., 2017). At the regional level, rural and urban development through job creation can be related factors (Diamantopoulou et al., 2016; Gaitan-Cremaschi et al., 2015; Helleno et al., 2017; Karvonen et al., 2017; Vinodh & Girubha, 2012). At the national level, self-reliance on energy and security are important (Karvonen et al., 2017)

On an individual level—Personal growth can be associated with establishing a successful industry in an area. Depending on the culture, quality of life, education, and politics of a region, social inclusion/acceptance can be determined. The same is true for consumption experience and access to new lifestyles (Diamantopoulou et al., 2016; Xia et al., 2017). For an individual, "personal growth" cannot be measured through one metric, as this concept is highly complex and subjective; therefore, research in this area could be hindered by data disaggregation (Church & Rogers, 2006). To some people, the opportunity to earn more money is the most important result. For others, improved health, peace of mind, acquiring new skills, achieving work-life balance, and other issues play a role in personal growth. Since this paper covers several of these aspects under other pillars, personal growth of employees was not considered a separate indicator under development. There is, however, an emerging concept called "self-quantification" that allows individuals to use data in daily life to determine improvement or regression (Wolf, 2010). Smartphones and smartwatches now cater to this movement through several fitness applications to monitor health and daily schedules. Currently at the beginning of a "Fourth Industrial Revolution," which consists of a fusion of technologies that combines the physical, digital, and biological spheres that earlier shaped the first (steam for industry), second (electricity for mass production), and third (information technology and automation) revolutions and blurs the lines between them (Keywell, 2017; Schwab, 2016). This fusion can provide companies with avenues of opportunity to assist them in determining employee well-being through proper channels of communication and transparency.

The interrelationships among industry clusters are known to instigate innovation and boost local job markets (Clusters 101, 2014). With respect to biobased industries, it is worth noting how materials, services, and products are circulated based on research and application-based requirements, with resulting effects on people. Realizing that development goes hand in hand with the natural environment, there has been a push to study social angles. The Human Development Index (HDI) is one such factor; it is meant to "reflect life expectancy, literacy and command over resources to enjoy a decent standard of living" and "capture the many dimensions of human choices" (Sen, 1994; UNDP, 1990). The HDI looks at regional development through a humanistic perspective, including social relationships and quality of life. For this reason, HDI was chosen to represent regional development with respect to biobased industries. Although this is a step toward a holistic perspective on development, factors such as participation in decision making and respect are yet to be incorporated, and they prove to be difficult to quantify (Vujnić, 2014). Such factors are incorporated herein in an effort to introduce such quantification. Aggregating the points above, the indicator chosen for the category **Regional development** is ***regional HDI.*** It is expressed as *regional HDI =* $(I_1 + I_2 + I_3)/3$ *where* I_1*—Life Expectancy Index: Average number of years from the time of birth to death;* I_2*—Education Index: Adult literacy rate (%) + gross enrollment ratios of students in primary school through university level;* I_3*—gross domestic product index: GDP*/capita in purchasing power parity terms, based on USD.* Tables and the full methodology are provided (Tables SI-4 and SI-5) under Section SI-1 within the Supplemental Information section.

The last category under the social pillar deals with improving company reputation through transparency and accountability via several environmental certifications, third-party critical reviews, and annual voluntary sustainability assessments. This category is titled **corporate social responsibility**. Organizations can take various avenues to represent their dedication to sustainable products. One is eco-labeling, which provides information on the environmental performance of the product. Eco-labels can include certified Environmental Product Declarations (EPD) and/or Environmental Impact Assessments (EIA). Another is looking at pre-development activities and assessing the company's local and global environmental footprint based on various activities and LCAs to determine the overall holistic impact of a product through several verified methodologies. Some examples are ReCiPe with its eco-indicator point system, cumulative energy demand for EE with units in MJ, kWh or BTU, Impact 2002+, the GHG protocol for calculating GHG emissions, and water footprinting (ISO 9000, 2015; ISO 14025, 2006; ISO 14040, 2006; ISO 14044, 2006). Irrespective of the course of action, annual reporting is suggested to establish a baseline to improve upon previous assessments. This paper's aim is to support such sustainability reporting related to biobased products. For any sustainability reporting, transparency is key to developing trust within the company and among shareholders and clients. Transparency can be attained through the use of surveys and questionnaires for both workers and customers to fill out. ***Transparency*** was considered in several papers and has been chosen as an indicator in this paper; it is expressed in *% of indicators for which timely performance data are reported*. (Dale et al., 2013; Helleno et al., 2017; Kudoh et al., 2015; Latif et al., 2017). Using this unit for measurement leaves no room for greenwashed claims and results. Customer-supplier relationships play a role in determining how an organization's attitude moves toward sustainability. The indicator ***customer/supplier relationship*** is represented by the unit *number of customers with environmental requirements*, which can be further investigated with a weighted survey (Helleno et al., 2017; Heslouin et al., 2017; Huang & Badurdeen, 2017; Xia et al., 2017).

4.4 Indicators within the Economic Pillar

A company's earnings per share, often called the "bottom line," is considered one of the most important pieces of data reflecting a successful company. It refers to the income obtained by subtracting all company expenses from the gross revenue. Cutting expenses and increasing topline revenue (gross income) without increasing expenses are two methods of achieving a financially successful business (Investopedia, n.d.-a). However, as discussed earlier, financial status is not the only definition of a good business model in today's times. The stewardship and value associated with a product have just as much weight as monetary value, and each measure of success influences the other.

The first category within the economic pillar identified was **Profitability**, which can be defined as the difference between revenue (market price) and cost (expenditure of inputs at each stage) of a biobased industrial system (Gaitan-Cremaschi et al., 2015) (Table 5). Finances include an array of elements ranging from revenue to taxes, capital, operations, and miscellaneous expenses. Taxes and other costs related to operations, material acquisition, maintenance, energy, distribution, overhead, land, and labor are accrued on an annual basis. They need to be recorded and ready for annual financial review (Canciglieri et al., 2014; Eseoglu et al., 2014; Hallstedt, 2017; Helleno et al., 2017; Huang & Badurdeen, 2017; Joung et al., 2013; Kim et al., 2012; Kudoh et al., 2015; Nourmohamadi Shalke et al., 2017; Paju et al., 2010; Rasmussen et al., 2017; Smith et al., 2017; Vaidya & Mayer, 2016; Vinodh & Girubha, 2012; Xia et al., 2017). Other aspects that fall under this category have to do with pricing, competition, customer service, sales, and marketing (Eseoglu et al., 2014; Helleno et al., 2017; Huang & Badurdeen, 2017; Paju et al., 2010; Schöggl et al., 2017). ***Net present value (NPV)*** is the difference between the present value of cash inflows and the present value of cash outflows. Positive NPV points toward good investments in the long run (Investopedia, n.d.-b). ***Return on investment (ROI)*** acts as a performance measure to determine the efficiency of various investments by measuring the amount of profit on an investment relative to its cost (Investopedia, 2017). Although some papers brought in interesting alternative factors—such as national production rate, fossil energy ROI, Gross Domestic Product, gross value added, income diversification, impacts from eco-friendly investments, cost/benefit ratio, inflation, life-cycle costing, and analyzing competitive margins and market shares—ultimately NPV and ROI were chosen as appropriate indicators of profitability as they stand as good markers for the direction in which a company is headed (Dale et al., 2013; Joung et al., 2013; Karvonen et al., 2017; Mikko et al., 2013; Schöggl et al., 2017; Thevathasan et al., 2014; Valdez-Vazquez et al., 2017; Xia et al., 2017) They are expressed in *dollars ($)* or any regional currency.

Table 5. Economic categories with associated indicators and units for biobased product manufacturing

Category	Indicator	Unit
Profitability	Net present value	US dollars
	Return on investment	US dollars
Employment	Job creation	Number of jobs created in area (urban and rural)
Risk	Probability of risk in operations, weather events and supply chain	Fraction or percentage (%)

Another important aspect serving as a thread of the industrial fabric is **Employment,** which assesses not only the number of full-time and part-time workers but also benefits, compensation, how much commission or profit a worker makes, and other profit shares. Researchers have also investigated disposable income, purchasing power, and free time that workers have in their current jobs. Some of the more quantifiable attributes are labor intensity (person time/ha) and salary ($/day) (Dale et al., 2013; Gould et al., 2017; Helleno et al., 2017; Kluczek, 2017; Mikko et al., 2013; Vaidya & Mayer, 2016; Xia et al., 2017). The aim is to look at the effects of a biobased industry on select indicators, in this case, number of jobs created (within both urban and rural contexts) as a result of this industry. For this purpose, ***jobs created*** was chosen as an indicator and the unit *number of jobs created in area*.

"Risk" implies future uncertainty about deviation from expected earnings or expected outcome. It helps assess uncertainty, allowing investments to be made or rejected. Risks can arise as results of various scenarios, including business and insurance, liquidity, and—specifically in relation to biobased industries—weather conditions, crop failure, mismanagement, operation and processing failure, or other unpredictable delays (Definition of 'Risk,' 2017). Within the reviewed papers, risk is analyzed within several contexts:

1) Terms of trade ($ [net exports or balance of payments]), as trade volume, import/export change, and GDP (Dale et al., 2013; Karvonen et al., 2017), are considered as crops play a vital role as a foundation for any biobased system.
2) Food security is an important factor for consideration (% change in food price volatility), along with changes to regional food output and prices compared with past trends (Burli et al., 2016; Dale et al., 2013; Vaidya & Mayer, 2016).
3) Although this paper does not focus on producing biofuels, energy nonetheless poses a vital risk to the functioning of the chain. Local fuel mixes have the potential to influence how green a supply chain turns out to be when an LCA is performed. Hence, switching to more renewable resources is suggested. Energy security premium, rates of reduction of consumption, and inclusion of demand management in the project planning horizon are other issues to consider (Dale et al., 2013; Fortună et al., 2012).
4) Performance (as productivity) is a factor contributing to risk (Kudoh et al., 2015).
5) Resources can play a role in the number and types of contractors and processors, effects on community benefits (% of money generated remaining in local economy), and competition for resources (Lal et al., 2011; Vaidya & Mayer, 2016).

According to reasoning outlined above, it was decided to aggregate some of these influences for the **Risk** category and identify the indicator ***probability of risk*** with respect to operations, weather events, and supply chain, expressed as either a *fraction* or a *percentage*. As seen across various disciplines, the indicators listed for the Risk category are not evenly spread out. This accounts for the fact that there is no standardized format to determine indicators.

4.5 Sustainable Biobased Indicators

ASTM Standard E3066 (ASTM, 2016), Dale et al. (2015), and Dale & Beyeler (2001) were used as guiding documents for categorization and selection of indicators. After double filtration in which the first indicators from all the papers were listed and categorized under respective disciplines (manufacturing, materials, biomass) and pillars (environment, social, technical, economic), followed by another round of categorization to pool together those common units from relevant indicators (example: all GHG emissions–related terms were pooled into the GHG category, various power and heat sources were pooled into energy, and so on). Finally, these indicators were checked to determine points of overlap to understand how biobased indicators are valued across all three disciplines. Figure 3 below displays this overlap in the form of a Venn diagram.

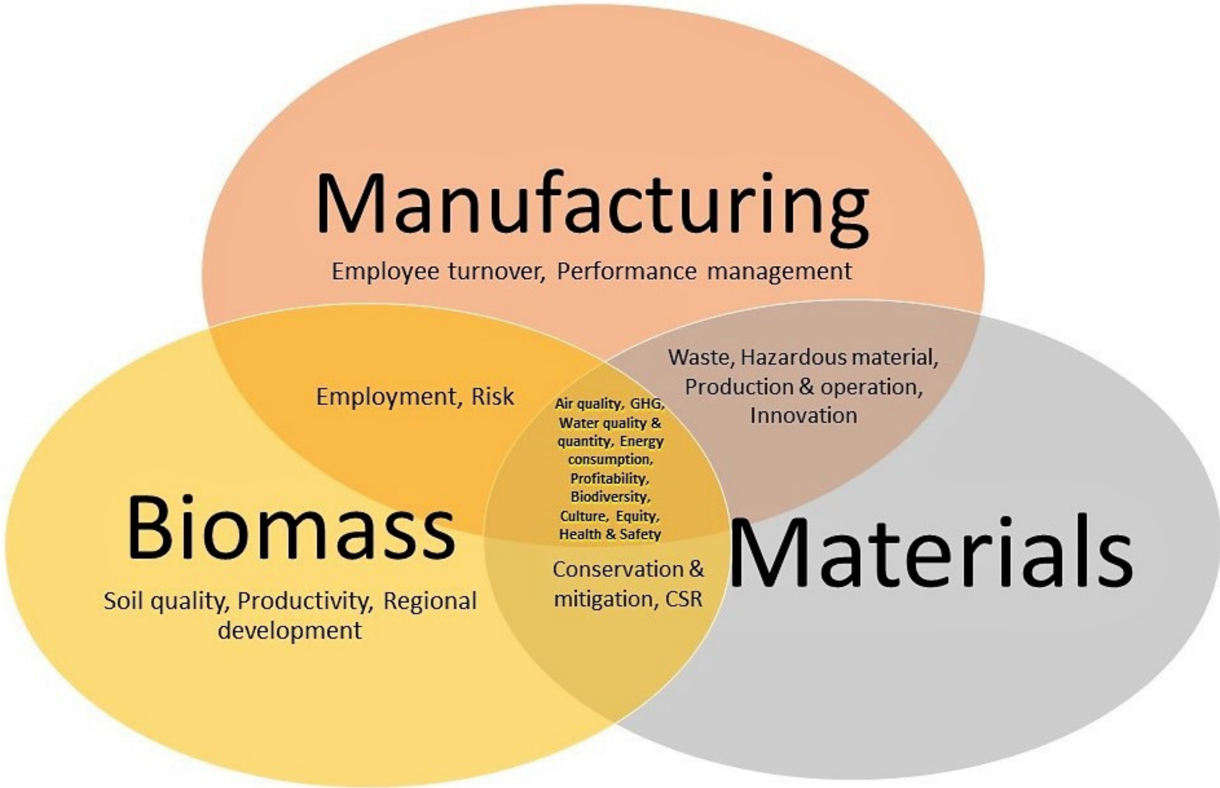

Figure 3. Venn diagram representing 22 categories within the disciplines of biomass, manufacturing, and materials

Following the categorization of indicators and their units among the three disciplines, the following relationships were observed:

1) The final sustainability indicators that are of interest to the biobased manufacturing sector from this systematic review and meta-analysis (as a result of overlap) across the three disciplines are **air quality, GHG, water quality and quantity, energy consumption, profitability, biodiversity, culture, equity,** and **health and safety.** These highlight the most valued aspects among these sectors with eight important indicators assessing the sustainability of a final biobased product. These factors are important for any industry to thrive, which is possibly the reason they overlap among the three disciplines. These indicators are the starting point in understanding the overall sustainability impacts of a biobased supply chain.

   Although according to sorting and categorization, the **GHG** category was found between Materials and Biomass, discussions with several environmentalists led this category to be placed in the center of the Venn on account of the shortage of time in addressing and rectifying these emissions through decarbonization efforts for both the economy and the planet alike.

2) **Soil quality, productivity,** and **regional development** were found to be exclusive to the biomass discipline, considering the importance of land and activities related to farming, harvesting, and yield and their effects on local communities.

3) **Employee turnover** and **performance management** were found purely within the manufacturing discipline. This could be a result of corporate influence within industries focusing heavily on structure within manufacturing, leading to a more organized human resources and management approach.

4) **Waste, hazardous material, production and operation,** and **innovation** were found to overlap between the materials and manufacturing disciplines. This could be due to consideration for indicators that are focused more toward synthetic manufacturing processes. Process and innovation are important to develop new and improved materials in industry

5) **Conservation and mitigation,** and **corporate social responsibility (CSR)** overlapped between the biomass and materials disciplines, indicating an inclination toward biomaterial development, marketing and outreach.

6) **Employment** and **risk** were found to overlap between the manufacturing and biomass disciplines, which indicates that jobs play a critical role in establishing these industries. It also represents the risks associated in relation to operations and the market.

7) It was interesting to note that the materials discipline exclusively did not have any indicators. Those that did, overlapped with other disciplines.

5. Conclusion

This study provides a starting point for researchers and industries interested in creating sustainable biobased products. With further analysis of supply chains, these indicators could represent areas of high interest, such as additive manufacturing, that lack sufficient quantified data. For example, analyzing the effects of a 3D printed biobased (bamboo–polylactic acid composite) product versus those of a conventional synthetic composite (carbon fiber–acrylonitrile butadiene styrene, or CF–ABS) or other natural fiber composite could prove useful in understanding the effects of energy, cost of operation, and health effects in relation to one another. Although this paper proposes a framework of sustainable indicators for consideration of manufacturing sustainable biobased products, it does not go into specific detail regarding manufacturing processes (3D printing, injection molding, lean manufacturing). Such papers looking at specific processes can be found under the "Extra References" tab of the Excel spreadsheet titled 'Data and Categorization' within Data files. It is important to recognize evolving ideologies such as 'post-normal science' that try to hybridize methods to approach real-world problems in a practical manner (Campos et al., 2017; Chen et al., 2017; Easterly et al., 2010; Feng et al., 2017; Ford & Despeisse, 2016; Funtowicz & Ravetz, 2003; Joung et al., 2013; Jovane et al., 2008; Paritala et al., 2017; Park & Kremer, 2017; GBEP Secretariat, 2011; Veleva & Ellenbecker, 2001). A case study involving a sustainability assessment of a biobased product demonstrating the use of the indicators presented in this paper would assist in representing those categories incorporated within each of the categories to determine areas of greater environmental impact.

The idea behind these indicators is that they collectively allow biobased industries of varying sizes to understand their baseline with respect to waste, energy, water, and other resource depleting-factors to enable rectification of such hotspots.

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