Proceedings of the 55th International Convention of Society of Wood Science and Technology
August 27-31, 2012 - Beijing, CHINA

Comparative Life-cycle Assessment of Sheet Molding Compound Reinforced by Natural Fiber vs. Glass Fiber

Jinwu Wang[1], Sheldon Q. Shi[2], and Kaiwen Liang[2]

1 Assistant Research Professor, Washington State University, Composite Materials and Engineering Center, P.O. Box 641806, Pullman, Washington, 99164-1806
jinwuwang@wsu.edu

2 Associate Professor and Assistant Research Professor, Department of Mechanical and Energy Engineering, University of North Texas, 3940 North Elm St., Denton, Texas 76207
Sheldon.shi@unt.edu, Kaiwen.liang@unt.edu

Abstract

The investigation is on comparative life-cycle assessments of three fiber-reinforced sheet molding compound (SMC) made from kenaf fiber, glass fiber and soy-based resin, respectively. SMCs for automotive applications are typically made of unsaturated polyesters and glass fibers. Using kenaf fiber and soy-based resin to partially replace the glass fiber and polyester resin is driven by their potential environmental benefits. A soy-based resin, maleatedacrylatedepoxidized soy oil (MAESO), was synthesized from refined soybean oil. SMC1 composite was made from kenaf fiber and polyester resin while SMC2 composite fromkenaf fiber and a resin blend of 20 % MASEO and 80% unsaturated polyester. SMC1 and SMC2 have both achieved substantial physical and mechanical properties, but were not yet comparable to a glass fiber reinforced polyester SMC in strength property (Springer, 1983, J. Reinforced Plastics Composites, 2(2):70-89). Thus, functional unit was defined as a mass to achieve the equal stiffness and stability when used to make interior parts for automobiles. The life-cycle assessments were conducted for three composites: SMC1, SMC2 and the glass fiber reinforced SMC. The materials and energy input/output of producing one functional unit of three composites were collected from lab experiments and literature. The key environmental measures were computed with SimaPro software. The results show that both kenaf fiber reinforced SMCs perform better than glass fiber SMC in every environmental category. The global warming potential of kenaf fiber SMC (SMC1) and kenaf soy resin based SMC (SMC2) were only about 45% and 58% of that for glass fiber SMC, respectively. This preliminary result has demonstrated that using soy-based resin and natural fiber for SMC would have a great ecological benefit.

Key words: Natural fiber; reinforced composites; sheet molding compound; life-cycle assessment.

Introduction

Sheet molding compound (SMC) is a mixture of molding resin, fibers, fillers, and additives. The traditional SMC molding resins for automotive applications are various unsaturated polyester resins (UPR) and vinyl ester. The reinforcementsareusually chopped short fiberglass and carbon fibers. Bast fibers such as kenaf have a similar morphology compared to the glass fibers, and their tensile strength and modulus are very attractive. Scientists are trying to find answers if these natural renewable fibers could replace the non-renewable glass fibers and plastic fibers. Various natural fiber reinforced polymer composites have been investigated using natural fibers such as kenaf, hemp, jute, and coir and commodity polymers such as polyethylene, polypropylene and unsaturated polyester resins (Holbery and Houston 2006; Kalia et al. 2011). However, no natural fiber reinforced composites achieved comparable physical and mechanical properties to glass fiber reinforced composites even in the laboratory with controlled process parameters. Especially, water resistance and impact toughness of natural fiber reinforced composites are far inferior to glass fiber composites (John and Anandjiwala 2008). The hydrophilic and intra-tangle characteristics of the natural fiber present challenges to disperse the fibers uniformly into the resin matrices in a scalable production. Although there is a need to improve current technology enabling natural fiber reinforced composites, this paper focuses on environmental impacts of the current technology of natural fiber reinforced composites.

The natural fiber reinforced composites have been generally perceived as renewable, biodegradable and environmentally friendly products. It is obvious that a technology utilizing the natural fibers to make composite materials reduces the global dependency on petroleum, however, quantitatively measurements of their environmentally friendliness are not fully conducted. It is not self-evident that it helps reduce the global carbon dioxide emissions since agriculture itself generates greenhouse gases due to the use of fertilizers, herbicides and pesticides and land clearing. While there is often an intuitively appealing or claims about renewability, biodegradability, and environmental friendliness of a product, process or service, the claims do not always stand up to an objective analysis. In addition, there is very little relevant data about what will happen at the end of life for these bio-based materials. If placed in a landfill, for example, off-gas is the natural by-product of the decomposition of solid waste in landfills and is comprised primarily of carbon dioxide and methane. Methane is a greenhouse gas and also an important energy source. When the conventional plastics are placed in a landfill, excavation data shows that they degrade very slowly with a time frame of 100 years. While this is not positive from a landfill capacity perspective, it does mean that carbon is sequestered and air and water pollution is minimized. In this sense, biodegradability is not a desirable feature of the product.

If landfill, however, installs a landfill gas collection system to collect and use landfill gas as a green energy source, generating electricity on-site which is then connected to the municipal utilities electric grid, biodegradability of materials will be beneficial to society. For example, the capacity of the electric generator fueled with the landfill gas in Denton, TX with a population of 113,383 in 2010 was 1.6 megawatts, powering the equivalent of approximately 1,600 homes per year (www.cityofdenton.com). In this sense, biodegradability and their rate of degradation are relevant to methane gas production rate and landfill capacity recovery. This unique effort to utilize methane emissions from landfill provides significant energy, economic and environmental benefits and justify biodegradable a desire feature for products.

Life-cycle assessment (LCA) is a standardized process for quantifying the life-cycle environmental impacts of materials, processes or services in terms of environmental impact indicators like global warming potential, embodied energy and embodied water. It consists of goal definition and scoping which defines the product, process or activity; inventory analysis which identifies material usage and environmental releases; impact analysis which assesses the human and ecological effects of energy, water and material usage; and last interpretation, which evaluates the results of each analysis. Integration of life-cycle analysis elements into early stages of materials development, product and construction designs will avoid short-lived, costly, and resource-intensive structures that generate negative environmental impacts. With a clear understanding of the most dominating causes of the environmental load in various life-cycle stages, it becomes easy to set priorities in the process or product improvement.

The overall goal of the project is to substitute of natural fiber reinforcement for glass fiber in thermoplastic or thermoset composites to achieve cost and weight savings without sacrificing the mechanical property requirements. This report investigates its environmental impacts, concentrating on the comparison of kenafbast fiber versus glass fiber as reinforcement in sheet molding composites (SMC),specifically,to determine if the use of kenaf fiber to replace glass fiber as reinforcement and the use of 20% soybean oil modified resin in fabricating SMC are advantageous from an ecological point of view.

Methods

A series of kenaf fiber reinforced SMCs have been fabricated in the laboratory for scoping and optimization. The life-cycle assessment was conducted on three product scenarios: Formulation SMC1 (kenaf fiber SMC), Formulation SMC2 (kenaf fiber 20 % soy resin SMC, blending 20% modified soybean oil with unsaturated polyester resin), and conventional glass fiber SMC. The life-cycle assessment of SMCs was assessed in two steps: (i) collecting life-cycle inventory (LCI) for material and energy inputs and emissions from SMC production processes, (ii) using an SimaPro model to perform environmental impact assessment for the emissions tabulated in (i). The LCA data for soybean oil resin and kenaf fiber reinforced composites were collected from lab syntheses. Actual industrial practices are expected to be much more energy- and material-efficient both currently and in potential future scale-up. The data for unsaturated polyester resin and glass fiber SMC were collected from literature(Liang and Shi 2010; Springer 1983). Other LCA data related with manufacturing raw materialswere collected from SimaPro software database (US LCI database andEcoInvent database). Catalysts and additives were not included as these materials represent less than 1% of the total material and negligible environmental impact. These data include energy and materials balances for manufacturing 1 kg raw materials, intermediates, and products, as well as emissions to air, discharges to water, and solid wastes to land. These data were then entered into the LCA software SimaPro V7.3. Environmental performances were measured by a set of environmental impact indexes came up with by NIST Building for Environmental and Economic Sustainability (BEES), cumulative energy demand and a weighted environmental burden.

Environmental Impact Assessment

Life-cycle impact assessment methods describe environmental impacts in terms of characterization factors. For a wide assessment of the environmental impact, the Building for Environmental and Economic Sustainability (BEES) set of impacts and Eco-indicator 99 were used. LCI results for the product comparisons are classified into impact categories, that is, categories in which a set of related flows may contribute to impacts on human or environmental health. Three types of environmental damages were considered: human health, ecosystem quality and resources. These damages are quantified by damage models. The Eco-indicator 99 Points were calculated by normalization and weighting of the damage factors. Ecoindicator single score is a tool to be used in the search for more environmentally friendly design alternatives and is intended for internal use. The scale is chosen in such a way the value of 1 Pt is representative for one thousandth of the yearly environmental load of one average European inhabitant (Goedkoop et al. 1999). The energy resource efficiency was assessed by the cumulated energy demand. The cumulated energy demand considered the entire demand of primary energy which flowed into the product system per functional unit (VDI 1997).

BEES has a recognized and accepted methodology to ensure a level playing field in terms of its methodological approach. All midpoint scores are expressed in units of a reference substance and related to the four damage categories human health, ecosystem quality, climate change, and resources as shown in Table 1(Lippiatt 2007). The global warming potentials (GWP) used by BEES were developed in 2001 by the International Panel of Climate Change. The 100 year GWP used are as follows: fossil carbon dioxide 1, methane 23, nitrous oxide 296, CFC/HCFCs 1700, methylene chlorine 10, HCFC22 1700. Biogenic CO_2 uptake is considered to be negative impact.

Table 1 Environmental impact indices

	Impact Category	Units
1	Global Warming	CO2 equivalents
2	Acidification	H+ equivalents
4	Human Health – Cancer	C6H6 equivalents
5	Human Health – NonCancer	C7H7 equivalents
6	HH Criteria Air Pollutants	microDALYs
7	Eutrophication	N equivalents
8	Ecological Toxicity	2,4-D equivalents
9	Smog	NOx equivalents
10	Natural Resource Depletion	MJ surplus energy
11	Indoor Air Quality	TVOC equivalents
12	Habitat Alteration	T & E count
13	Water Intake	liters of water
14	Ozone Depletion	CFC-11 equivalents

Results & Discussion

The LCA from cradle to gate for fibers and resins as well as comparative LCA of SMCs are summarized. The product with the highest impact is shown as representing 100%, while the impact of the other products is shown as a percentage of that value.

Fiber LCA

Fig. 1 indicates that kenaf fiber has less negative environmental impacts than glass fiber in stages from raw materials extraction to fiber manufacturing (cradle to gate). Fig. 2 shows that bast fibers (jute and kenaf) consume less energy than other fibers in manufacturing 1-kg fibers; most of consumed energy is renewable energy. Method to calculate the Cumulative Energy Demand (CED) was based on the method published by Ecoinvent version 2.0 and expanded by PRé Consultants for raw materials available in the SimaPro 7 database. CED has been the most important aggregated result of the inventory used for comparisons of product-related systems. The CED is the most meaningful parameter in judging the energy efficiency of systems since losses due to transformation and transport are fully taken into account. In addition to the cumulative process and transportation energy, it also contains the "feedstock energy", i.e. the primary energy equivalent of the materials produced from oil, coal, wood, etc

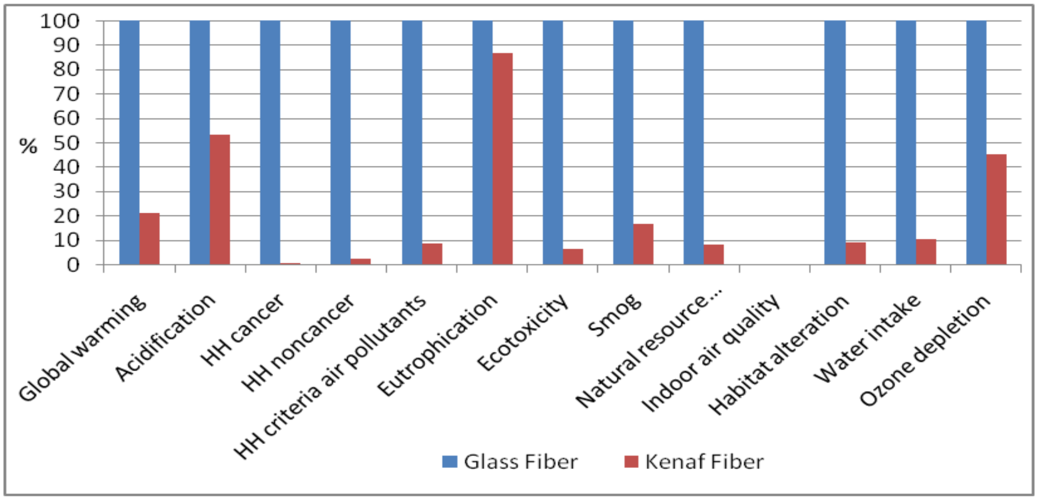
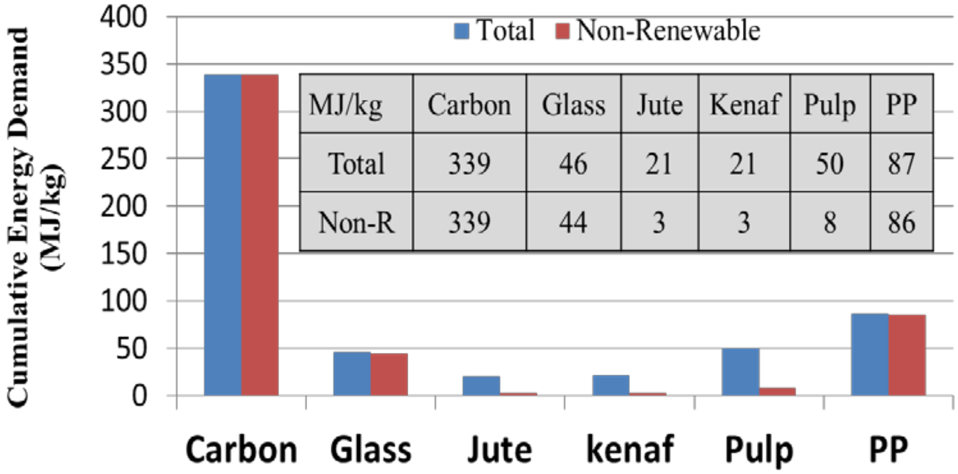


Figure 1 Comparison of environmental impacts of glass and kenaf fibers in BEES impact indices. Functional Unit: 1 kg fiber, Cradle to gate. Data: Kenaf Fiber, India; Glass Fiber, Europe.



MJ/kg	Carbon	Glass	Jute	Kenaf	Pulp	PP
Total	339	46	21	21	50	87
Non-R	339	44	3	3	8	86

Figure 2 the cumulative (primary) energy demand (CED) per 1-kg fiber.

Figure 3 indicates environmental burdons of different fibers from cradle to gate. One Pt represents one thousandth of the yearly environmental load of one average European inhabitant. Overall, fibers has a greater environmental impact in the category corresponding to its effects on respiration, mainly due to the releasing substances of an inorganic source such as particle matter, sulphites and nitrates. Another aspect worthy of mention is the consumption of fossile fuels for the petroleum-based fibers. Glass fiber has a substantial effect of carcinogens. Land use contributes substantial portions for agri-fibers. Fig. 3 demonstrates that natural fibers achieve overall lower environmental burdens. Land uses contributed substantial portions for agri-fibers (jute and kenaf).

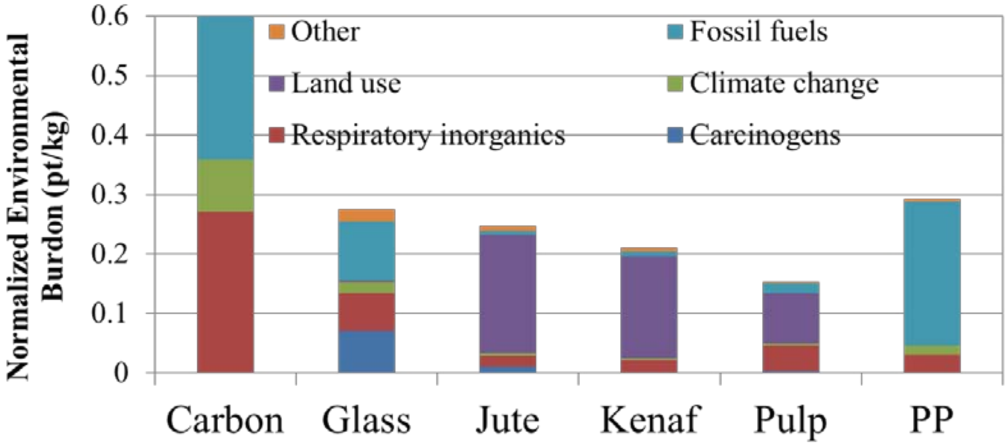


Figure 3 Comparison of environmental impacts of fibers in Eco-indicator 99 Points per 1-kg fiber.

Resin LCA

Figures 4,5 & 6 show comparisons of three resins in commulative energy demand, BEES emvironmental impact indices and Eco-indicator 99 Points. The use of fossil fuel in manufacturing resins contributes a large portion of environmental impacts.

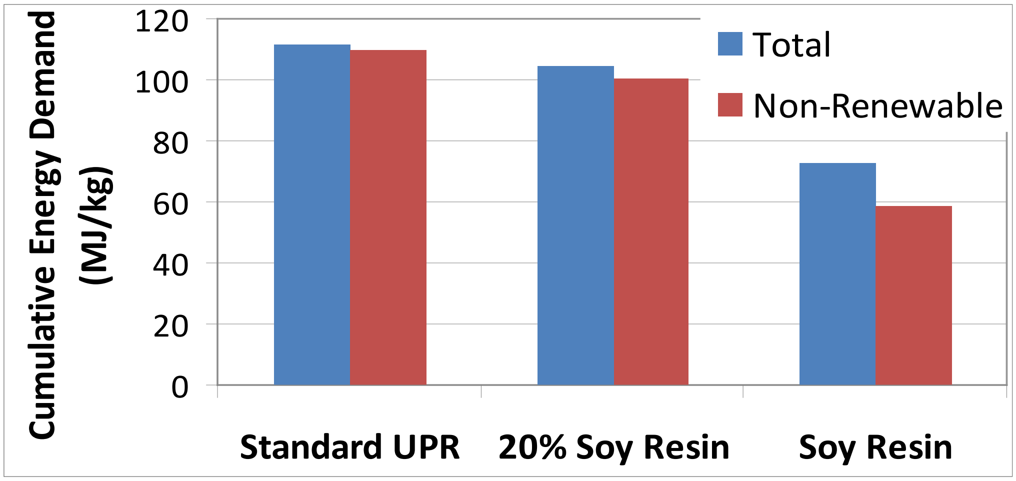


Figure 4 the cumulative (primary) energy demand (CED) of resins per 1-kg resin.

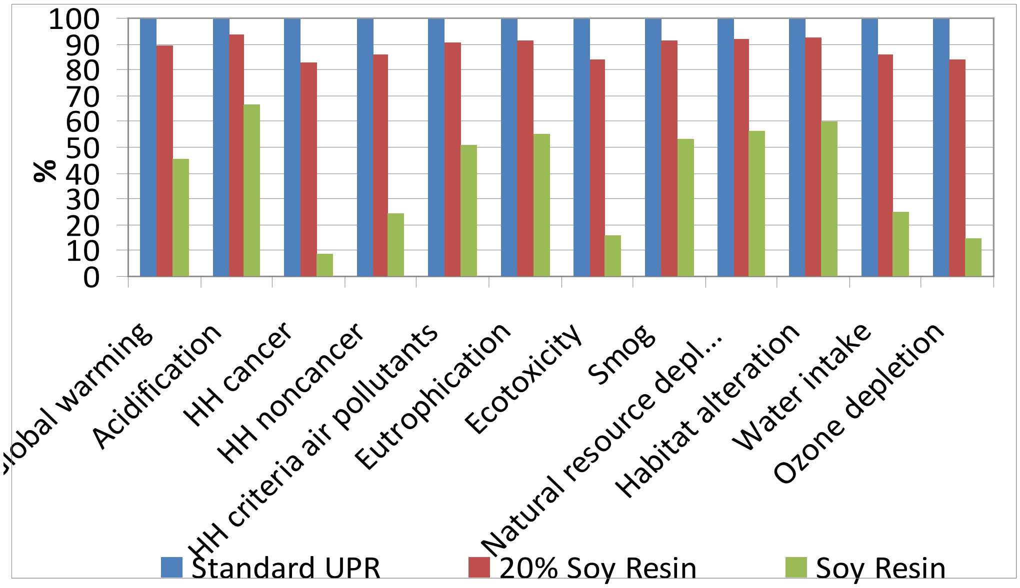


Figure 5 Comparison of environmental impacts of three resins in BEES impact indices.

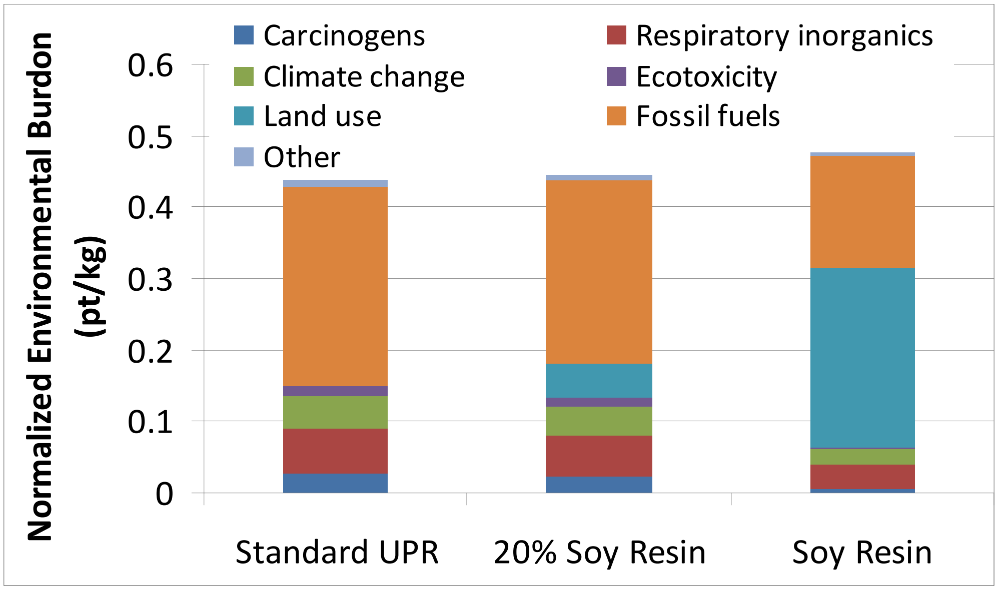


Figure 6 Comparison of environmental impacts of resins in Eco-indicator 99 Points per 1-kg resin.

LCA of SMC

The key environmental measures for three product scenarios were computed withSimaPro software and are shown as in Fig. 7. Both kenaf-fiber reinforced SMCs perform better than glass fiber SMC in every environmental category. The global warming potential of the kenaf fiber SMC (SMC1) could be only about 45% of that for the glass fiber SMC. The global warming potential of the kenaf fiber soy-resin composites (SMC2) is slightly higher than that of kenaf fiber SMC due to the agricultural production of soybeans.

Negative means carbon credit, i.e. saving non-renewable resources otherwise being used due to the energy recovery at the end-of-life disposal. Overall, the inclination at the end of the life of the kenaf and soy resin contained composites generates additional energy. In SimaPro program, this additional energy is treated as a substitute of fossil resources to significantly reduce the impact associated with the categories of acidification, air pollutants, and smog. Furthermore, using resources beyond their rate of replacement is considered to be resource depletion. Kenaf and soy are annual crops, if coming from sustainable farming, which does not contribute to natural resources depletion.

Conclusions

This preliminary result has demonstrated that the use of modified soybean oil and natural fiber to make sheet molding compound had a great potential from an ecological point of view. LCA is an effective tool to analyze environmental impact of the developed materials and products. Life-cycle thinking and assessment can be a great educational tool to promote renewable bioproducts.

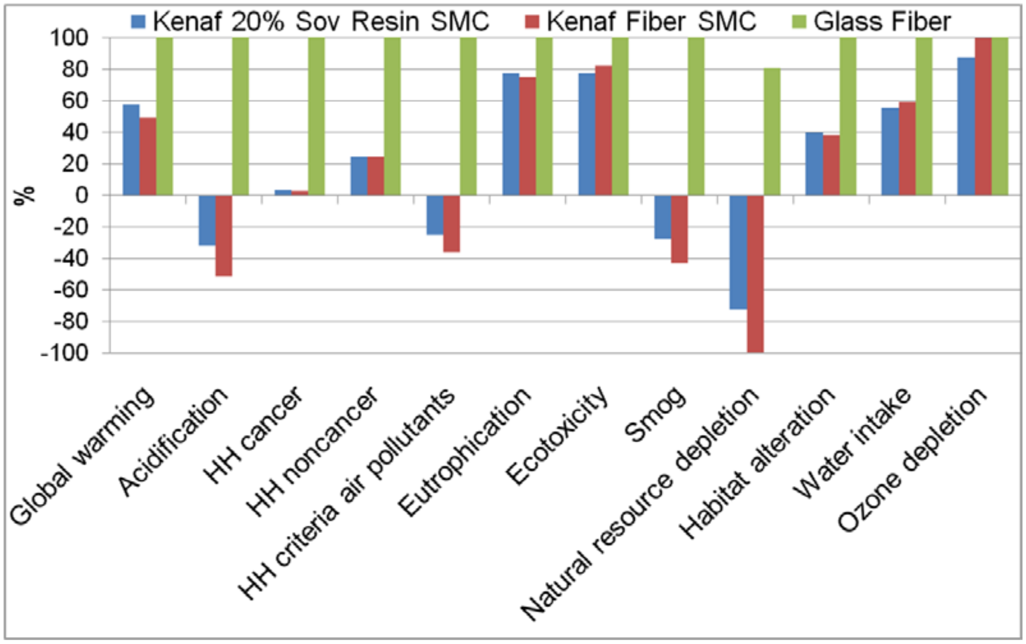


Figure 7 Relative Contribution of three SMCs per 1 functional unit

Acknowledgement

The research work was supported by Department of Energy (DOE), funding # 362000-060803 through Center for Advanced Vehicular System (CAVs) at Mississippi State University. Acknowledges are given to Dr. Philip Steele and Dr. Jerome Cooper for providing the LCA SimaPro software.

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