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ORIGINAL PAPER

Comparative life cycle assessment of beneficial applications for scrap tires

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Abstract Life cycle assessment is used to determine the most environmentally beneficial alternatives for reuse of scrap tires, based on the concept of industrial ecology. Unutilized scrap tires can be a major source of pollution, and in the past decade Federal and state governments in the United States have encouraged the recycling and reuse of scrap tires in a number of applications, ranging from energy recovery to civil engineering materials to utilization of ground rubber in manufacturing. Life cycle inventory data are collected from primary industry sources as well as published literature, and life cycle impact analysis is performed using the TRACI tool. The results indicate that beneficial reuse of scrap tires, particularly in cement plants and artificial turf, provides reductions in greenhouse gas (GHG) emissions, air toxics, and water consumption. For example, every metric ton of tire-derived fuel substituted for coal in cement kilns avoids an estimated 543 kg (CO_2 equivalent) of direct and indirect GHG emissions. Taking into account the deductible CO_2 from natural rubber, the avoided GHG emissions would be 613 CO_2 kg eq. per metric ton. The use of scrap tires for fuel in cement plants provides more reductions in most environmental impact categories compared to other scrap tire applications, excluding application in artificial turf. Although the use of ground rubber for artificial turf offers the greatest environmental emission reductions, it has limited potential for large-scale utilization due to the saturated market for artificial turf. Therefore, the use of fuel derived from scrap tires in cement production appears to be an attractive option in view of its large market capacity and significant potential for environmental impact reductions.

Keywords Life cycle assessment · Scrap tires · Tire-derived fuels · Tire-derived aggregates · Ground rubber · Cement production · Alternative fuels · Raw materials

Introduction

With increasing concerns about the sustainability of industrial supply chains, both government and private sector organizations are making efforts to improve the management of solid wastes. One of the most beneficial approaches to solid waste reduction is *industrial ecology*, a practice inspired by the waste-free material cycles found in nature (Chertow 2007; Fiksel 2002). Industrial ecology involves the conversion of wastes into by-products that can be used as feedstocks for other industrial processes. Scrap tires are an excellent candidate for industrial ecology, since they can be shredded, ground, and utilized in a variety of applications as fuels or raw materials. By displacing virgin materials, including fossil fuels, such applications are expected to reduce overall environmental impacts.

Abandoned or stockpiled scrap tires can be a source of breeding grounds for vectors such as rodents and mosquitoes. The curvy structures of scrap tires create stagnant water pools, making them an ideal place for breeding. Mosquitoes are known to carry fatal diseases such as

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Dengue Fever and Encephalitis. Moreover, stockpiled scrap tires are susceptible to fire hazards due to their heat-retaining characteristics. The smoke from tire fires includes hazardous compounds (polycyclic aromatic hydrocarbons or PAHs, benzene, styrene, phenols, butadiene, etc.), metals, and oils due to lower combustion temperatures, which can contaminate air, soil, and water. In contrast, temperatures in cement kilns, boilers, and incinerators are very high, leading to reduced emissions of hydrocarbons. It should be noted that annual cleanup costs for tire fires run into millions of dollars in the United States (EPA 2008). Because of serious environmental problems and potential benefits from recycling, 48 states have implemented laws or regulations that govern the collection, handling, recycling/reuse, and disposal of scrap tires. Some states including New York, Vermont, and New Jersey have passed legislation that provides grants, subsidies, and market incentives for reuse and recycling of scrap tires (RMA 2007).

Landfill disposal is the default option for scrap tires that are not recycled and reused. However, scrap tires are prone to uneven settlement and a tendency to "float", thereby threatening landfill covers; therefore, it is recommended that scrap tires be shredded prior to disposal. In recent years, there has been increasing disposal of shredded tires in monofills, i.e., landfills designated for only one type of material. In order to avoid complications from disposal of scrap tires in landfills, 38 states do not allow the placement of whole tires in landfills. Only 35 states allow landfilling of shredded tires, whereas 11 states ban the landfill disposal of scrap tires in any form (EPA 2008).

The purpose of this study is to compare the environmental benefits of different scrap tire applications, using life cycle assessment (LCA) methodology. The applications studied include tire-derived fuel, civil engineering, and use of ground rubber for production of artificial turf, asphalt, molded products, and tire retreading. All of these applications represent cost-effective options to avoid landfill disposal of scrap tires. The study findings indicate significant opportunities to reduce energy consumption, solid waste generation, and other environmental burdens by extracting residual value from tires at the end of their useful life.

Beneficial applications of scrap tires

Nearly 290 million used tires were classified as scrap in the United States in 2005, the latest year for which data are available. Scrap tires are defined as "unwanted or discarded tires, regardless of size" that are no longer used for their original purpose (Ohio EPA 2007). Scrap tires include whole tires, as well as pieces of whole tires that still contain steel wires and can be visually identified as scrap tires. Scrap tires have been utilized for energy generation in incinerators, power plants, and cement plants, and for various applications in civil engineering, tire retreading, and molded product manufacturing. As shown in Fig. 1, the percentage utilization of scrap tires has increased over the years due to both environmental concerns about tire disposal and the economic benefits of scrap tire reuse. The Rubber Manufacturers Association (RMA) attributes the increase in utilization of scrap tires to expansion in the scrap tire markets for tire-derived fuel (TDF) and coarse rubber applications (RMA 2006).

Today, the three major applications of scrap tires, as shown in Fig. 2, are tire-derived fuel, civil engineering applications, and ground rubber. Together, these applications accounted for about 80% of all scrap tire recycling in 2005, while approximately 14% of scrap tires were disposed on land. The following is a brief discussion of the above three applications.

Tire-derived fuel (TDF) mainly refers to shredded tires but whole tires can also be used as a fuel. As of 2005, more than 50% of the tires produced in the United States were diverted to energy use as TDF. Not only does TDF replace fossil fuels, but also it generates about 23% less CO_2 per joule of energy used as compared to coal (WBCSD 2005). Utilization of TDF may reduce NO_x and SO_x emissions particularly if it is used in place of high sulfur coal. About 27% of TDF comes from renewable biomass. i.e., natural rubber, and CO_2 emissions from combustion of this biomass portion can be regarded as zero since an equivalent amount will be sequestered by rubber plants. This further reduces the net CO_2 emissions from TDF use. Finally, ash obtained from combustion of TDF and coal in cement kilns gets incorporated into cement thereby eliminating the disposal of ash. The growth trends in TDF applications are shown in Fig. 3. This study includes a comparative analysis of the environmental impacts of using TDF in cement production, industrial boilers, and waste-to-energy facilities.

Civil engineering applications using Tire-Derived Aggregates (TDAs) constitute the second major use of scrap tires in the United States. TDA materials assist in construction of thin and less expensive walls and avoid the problem of frost formation. They weigh 1/3–1/2 as much as soil and their drainage and insulation properties are superior to those of soil and gravel. Environmental studies indicate that there would be limited impacts on drinking water quality and aquatic species from the use of TDA (Humphrey and Swett 2006). TDA applications have decreased by 6% from 2003 to 2005, mainly due to the shift toward TDF, which provides greater return on investment. The major TDA applications are for landfill construction and operation, septic system drain fields, and highway embankments or fillers. The two representative applications chosen for this study are the use of TDA as a replacement for sand in lightweight backfill and as a replacement for gravel in leachate collection systems.

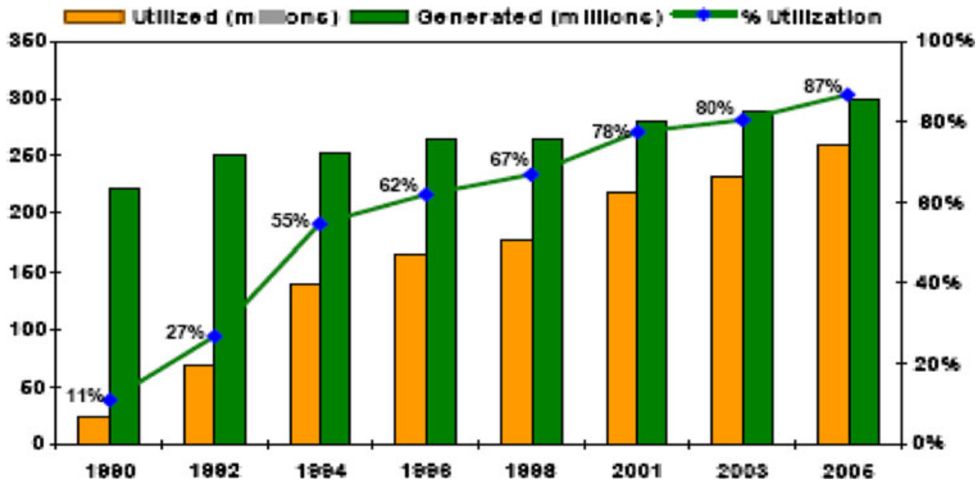


Fig. 1 Scrap tire generation and utilization in the US market (RMA 2006)

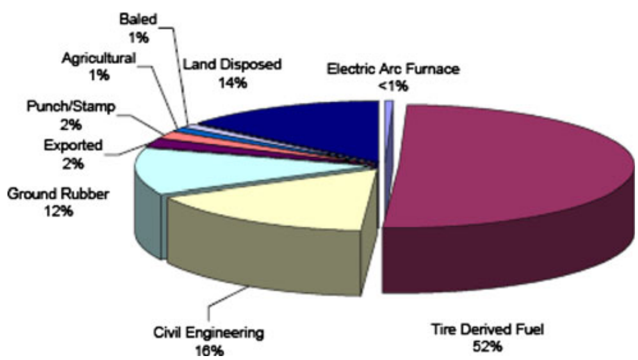


Fig. 2 Distribution of scrap tire applications (RMA 2006)

Ground rubber applications include athletic/recreational facilities, molded/extruded products, asphalt production, and tire retreading (see Fig. 4). Use of scrap tires in asphalt production enhances durability of road surfaces, minimizes road noise and maintenance costs, and reduces braking distances. Likewise, scrap tire use in recreational and athletic surfaces adds beneficial properties such as increased resiliency and high impact attenuation, thereby lowering the incidence of injuries. A California study (OEHHA 2007) investigated possible health hazards to children from recycling scrap tires in playgrounds due to oral and dermal exposure. The study concluded that the risks posed by exposure to rubber were within acceptable limits, and that use of scrap tires will not have detrimental effects on the local environment and ecology. There are continuing concerns about exposure of athletes to infectious diseases from bacteria that are harbored in artificial turf (Claudio 2008). The LCA described here focuses on ground rubber uses for artificial turf, asphalt, molded products, and tire retreading.

Life cycle assessment methodology

This study was conducted in adherence with standard LCA guidelines (ISO 14040:2006 and ISO 14044:2006)

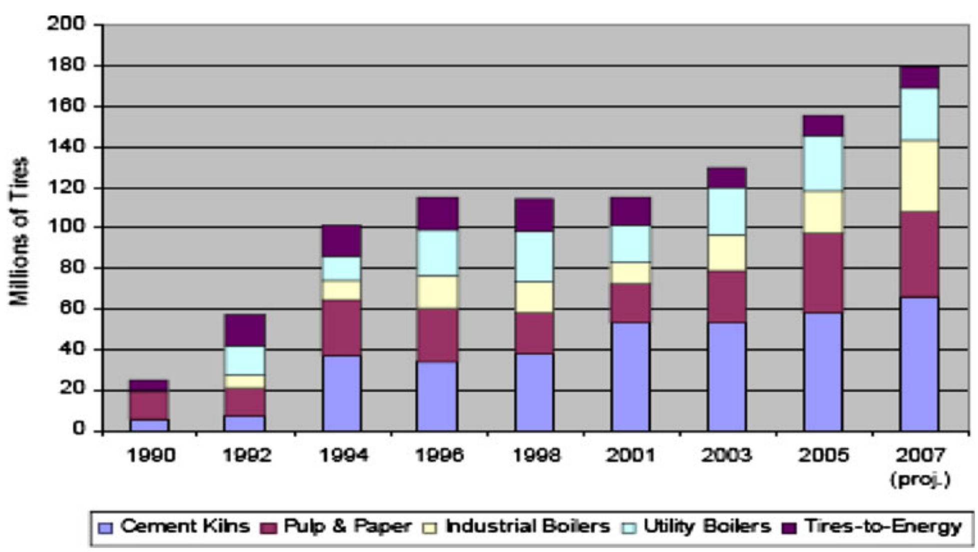


Fig. 3 Distribution of TDF applications (RMA 2006)

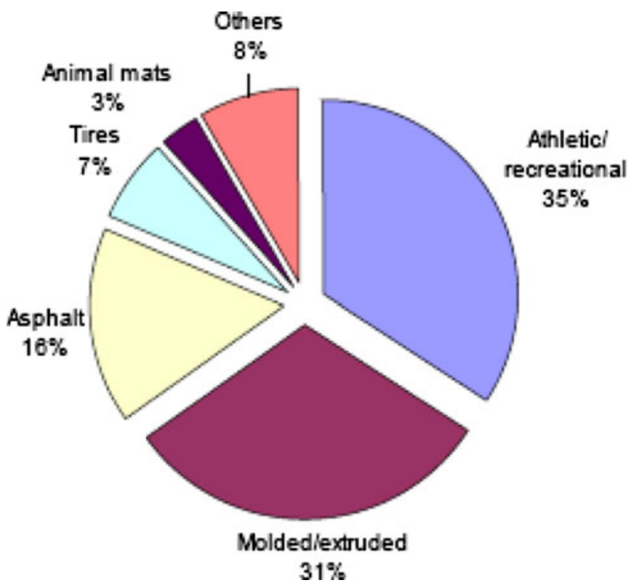


Fig. 4 Distribution of ground rubber applications (RMA 2006)

developed by the International Organization for Standardization. These guidelines require that (a) the goal and scope of the project are precisely defined; (b) assumptions are transparently stated, and the system boundaries, functional unit, and other pertinent aspects of the study are defined and described, and (c) relevant data are collected, their quality is rigorously assessed and data gaps are noted.

Goal and scope

The *goal* of the study is to compare the environmental benefits resulting from the utilization of scrap tires for various applications. The *functional unit* for this study is the utilization of 1000 kg of scrap tires. The results presented here compare the relative environmental benefits of utilizing 1000 kg, i.e., 1 metric ton (MT), of scrap tires in different applications. Figure 5 shows the alternative end-of-life pathways for scrap tires corresponding to these applications, including transport of scrap tires and derived byproducts. Note that shredded tire production is an input to ground rubber production. The base case and alternative scenarios for the LCA of these scrap tire applications are described in Table 1.

Data sources, assumptions, and uncertainties

Emissions and resource consumption data associated with the inputs to each process are obtained using NREL or SimaPro databases (see Table 1). They are combined with operational data obtained from primary industry sources and published literature. For cement plant, boiler, and waste-to-energy applications, airborne emissions from the operation phase are included. For the rest of applications

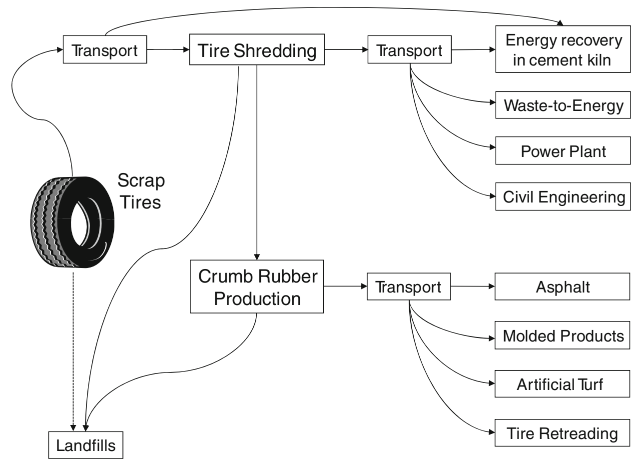


Fig. 5 Alternative end-of-life pathways for scrap tires

excluding asphalt and tire retreading, only emissions and resource consumption associated with extraction and production of inputs are considered; the study does not analyze the subsequent production and use phases. For example, when shredded tires are used as replacement for gravel in a leachate collection system, the study considers only the differences in how scrap tires and gravel are produced, not their impacts on the operation of a leachate collection system. *The underlying assumption is that substitution of shredded or ground rubber does not affect the subsequent operational performance or environmental impacts of the product or process applications considered.* This assumption may not hold in some cases; for example, the performance of asphalt that incorporates ground rubber may be different. Likewise, the emissions from end-of-life disposition of molded products that incorporate ground rubber may be different.

Life cycle inventories (LCIs) are developed using data collected from industry contacts, industry associations, and published literature (see Table 2). In addition, primary data were collected from manufacturing firms or facility managers for each application type. Inventory data were collected in the following categories: methane, carbon dioxide, criteria pollutants (excluding ozone), heavy metals (airborne), dioxins, other air pollutants, emissions to water, emissions to soil, solid waste generation, and water consumption. The specific types of emissions for each process are identified in the "Process characterization and system boundaries" section, and the resulting LCI data appear in the "Summary of life cycle inventory results" section. The LCI data serve as the basis for the life cycle environmental impact assessment in the "Life cycle impact assessment results" section.

In order to ensure meaningful results, data quality was emphasized in this study. Precision of the data are generally good, since they are derived from a combination of

Table 1 Base cases vs. alternative scenarios for various scrap tire applications

	Base case	Alternative	Limitations
Artificial turf	EPDM	Crumb rubber	Emissions from construction & use of artificial turf excluded
Asphalt	Without crumb rubber	With crumb rubber	Emissions from use of asphalt excluded
Tire retreading	Synthetic rubber	With crumb rubber	Emissions from use of retreaded tire excluded
Molded products	• Molded EPDM	Molded crumb rubber	Emissions from molding & use of molded products excluded
	• Molded LDPE	Molded crumb rubber	Emissions from molding & use of molded products excluded
	• Molded HPDE	Molded crumb rubber	Emissions from molding & use of molded products excluded
	• Molded SBR	Molded crumb rubber	Emissions from molding & use of molded products excluded
Lightweight backfill	Sand	Shredded tires	Emissions from construction and use of backfills excluded
Leachate collection system	Gravel	Shredded tires	Emissions from construction and operation of leachate collection system excluded
Incineration	Municipal solid waste	Municipal solid waste plus shredded tires	Emissions from combustion of municipal solid waste & scrap tires included. Data used refer to the differences between the base case and alternative; absolute data are not available
Industrial Boiler	Coal	Coal plus shredded tires	Solid waste generated from a boiler not included
Cement plant	Coal plus petcoke	Coal, petcoke, whole or shredded tires	

primary sources and reliable databases (see Table 1). Completeness of the data is satisfactory, although a number of data gaps were encountered, as shown in Table 2. The consistency of the data is maintained through the use of similar sources, scope of analysis, and level of detail for each process studied. The results are fully reproducible by experienced LCA experts, and the complete input dataset can be obtained on request. The data are representative of the time period 2000–2008, and the geographic coverage is North America. Apart from the cement manufacturing processes, the data are not necessarily representative of the full range of available technologies.

The allocation method used for multiple output streams (co-products) is mass-based allocation, although other methods are available (Heijungs and Guinee 2007). In mass-based allocation, the inputs and outputs are allocated based on the proportion of the total mass of the co-products. For example, if there are two co-products A and B, then the fraction allocated to Product A is given by,

$$\alpha_A = \frac{m_A}{m_A + m_B}$$

where m_A and m_B represent the mass of Product A and B, respectively.

Life cycle impact assessment (LCIA) is performed to evaluate the significance of material flows quantified by LCI. Udo de Haes et al. (1999a, b) provide a survey of commonly practiced impact assessment methods as well as the impact categories available. In this study, the TRACI methodology (Bare et al. 2002) was chosen to quantify the impacts, since it is publicly available from U.S. EPA and one of the most widely used methods in North America. (TRACI stands for Tool for Reduction and Assessment of Chemical and Other Environmental Impacts.) TRACI facilitates the characterization of environmental stressors that include ozone depletion, global warming, acidification, eutrophication, tropospheric ozone (smog) formation, ecotoxicity, human health criteria-related effects, human health cancer effects, and human health non-cancer effects. The total impact scores for each of these categories are obtained by calculating the individual impacts based on the emissions of each substance and its characterization factor; and adding the corresponding impacts under each category.

Interpretation entails a review and examination of LCIA results including major contributing factors, investigation of sensitivity and uncertainty analysis, and formulation of conclusions. In this study, sensitivity analysis was performed for cement applications to obtain a range of values reflecting actual variations in inputs and outputs corresponding to three kiln types. While sensitivity analysis was not performed for the other applications, it is expected that variability will be small for civil engineering applications and substitution of molded products, since there are a small number of inputs whose values are fairly well known. Uncertainties are limited mainly to upstream emissions associated with input data that were obtained from NREL and SimaPro. Other potential sources of uncertainty include unknown data gaps and assumptions incorporated into the impact assessment methodology.

Table 2 Sources of life cycle inventory data for scrap tire applications

	Primary data sources	Association contacts	Data bases	Published sources	Data gaps for emissions
Cement production	Holcim (US); ETH Zurich	Portland Cement Association (PCA)		Boesch (2008)	Only NH3, HCl, HF data for production
Civil engineering	Rubber Manufacturers Association (RMA)	Michael Blumenthal, RMA	NREL, SimaPro		No solid waste data
Incineration	Tire Industry Association (TIA)	Mike Sikora, TIA	NREL, SimaPro	Corti and Lombardi (2004)	Incineration: no CO; metals limited to Cu, Cd, Hg, Pb[b]
Industrial boiler			SimaPro	Reisman (1997)	No emissions to soil and water, water use, solid waste[b]
Tire shredding and crumb production	Crumb rubber manufacturer, Ohio; RMA, TIA	Michael Blumenthal, RMA; Mike Sikora, TIA; RMA Division of AIChE	NREL, SimaPro	Corti and Lombardi (2004)	No gaps
Artificial turf	Turf manufacturer, GA	Michael Blumenthal, RMA; Mike Sikora, TIA	NREL, SimaPro		No gaps
Molded products	Two manufacturers, RMA Div. of AIChE.	Michael Blumenthal, RMA; Mike Sikora, TIA;	NREL, SimaPro		No solid waste data for EPDM
Asphalt production	Rubber Pavements Assoc. (RPA), Manufacturer, NM	Doug Carlson, RPA	NREL, SimaPro		No gaps for mining and production of inputs[a]
Retreading	Tire Retread Info. Bureau (TRIB); Manufacturers	Harvey Brodsky, TRIB	NREL, SimaPro		No gaps

[a] Metals, dioxins, other air pollutants, emissions to water & soil, and solid waste data are unavailable for asphalt production stage

[b] Only HCl and HF data were available under other air pollutants; methane emissions estimated at 16% of VOCs

Process characterization and system boundaries

Cement production

The cement production process consists of three major steps: quarrying and raw materials preparation, clinker production, and cement grinding and distribution. In the clinker production step, limestone, clay and alternative raw materials are mixed and homogenized, then milled and dried, and the resulting mixture is preheated before entry into the kiln. In the kiln, where the flame temperatures reach 2000°C (3632°F) and the material temperatures reach 1450°C (2642°F), the raw materials are transformed into clinker. In the clinker cooler, the molten clinker is rapidly cooled, and ground with 5% of gypsum and other materials such as slag or fly ash to form the final cement powder, which is packaged in bags for transport (PCA 2008).

In this study, three major kiln types are considered: Long Wet Kiln, Long Dry Kiln, and Precalciner Kiln. For purposes of inventory development, data for eight Holcim (USA) cement plants representing the three kiln types were averaged, based on data provided by ETH Zurich (Boesch 2008). In the base case, the extraction and pre-processing of coal and petcoke were considered, along with the clinker production process and cooling of clinker. For the alternative case, the processes associated with scrap tire handling are included, as shown in Fig. 6. Some plants use scrap tires directly while others process them into shredded tires before combustion; since electricity use in pre-processing is relatively small, the difference is negligible. Process raw materials such as limestone, clay, and iron ore were included in the inventory. Soil and water emissions from cement plant operations are considered to be negligible.

Incinerators and boilers

Besides cement production, this study considers the use of tire-derived fuel (TDF) in municipal solid waste (MSW) incinerators and industrial boilers. The former use coarse shredded tires, but the size of shredded tires required for

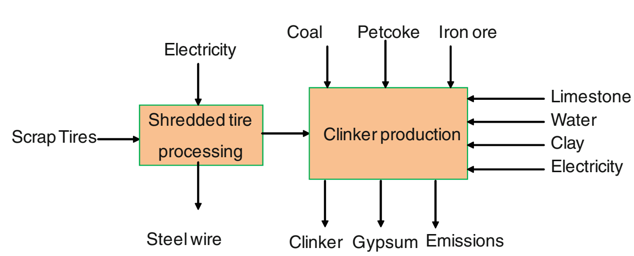


Fig. 6 System boundary for tire-derived fuel use in cement production

boilers is considerably smaller than for waste-to-energy facilities (Corti and Lombardi 2004). Therefore, the shredded tires require secondary processing that produces two different sizes of shredded tires: less than 1½ inch and greater than 1 ½ inch. The smaller size is used for boilers, and the larger size for civil engineering applications. Steel wire is separated from the tires, and is sold separately as a byproduct.

Boilers generally use coal as the main fuel to generate electricity and steam. The study data are based on a boiler located at the University of Iowa (170,000 lb/hr capacity, Riley-1975), where coal along with TDF is used to generate steam. The fuel mix for the alternative scenario involves 92% coal and 8% TDF. The combustion products, cinders and bottom ash, are treated as solid waste, although it is possible to recycle coal combustion products.

The scope of this study includes the relative differences in airborne emissions due to substitution of TDF for coal, but not in the solid or liquid wastes. Process air emissions were modeled after the emissions reported by Reisman (1997) for the Iowa boiler. CO_2 emission data are not available, and were estimated based on CO_2 emissions from cement plants by taking into account the amounts of coal and TDF used. Soil and water emissions from the boiler were not included due to lack of data. It is assumed that the distances traveled and amounts of municipal solid waste and TDF transported are similar, and hence transport is ignored. Incineration of MSW including TDF requires more soda and therefore, emissions associated with the transportation of soda were considered in the analysis.

Civil engineering applications

In civil engineering applications, finely shredded tires replace conventional sand or gravel. Specifically, in lightweight backfill shredded tires replace sand, and in leachate collection systems they replace gravel (Grimes et al. 2003; Blumenthal 2007). This study compares the environmental impacts of producing shredded tires against impacts of mining sand and gravel. The study accounts for the fact that it takes nearly 3.5 times more sand or gravel to fill the same volume when compared with shredded tires. As stated in the "Life cycle assessment methodology" section, the operational phase of the civil engineering systems was excluded from the scope.

Asphalt production

In asphalt production, crumb rubber is blended with asphalt and used with gravel. For this study, production of asphalt was compared for the cases with and without crumb rubber. Crumb rubber manufacturing is accomplished by placing shredded tires into a fine grind process, producing different sizes of crumb rubber; the size of crumb rubber used in asphalt production is less than 8 mesh size. The fine grind process generates steel wires, which are sold separately, and textile fibers, which are treated as solid waste.

Figure 7 shows the process flow for asphalt production both with and without crumb rubber. Gravel sorted in the scalping screen is mixed with asphalt in the drum dryer and the resultant mixture is stored in silos. Crumb rubber is blended with asphalt in a separate process before being mixed with the gravel.

Molded products

Crumb rubber has begun to replace conventional plastics and rubber in several molded products. According to RMA, there is no appreciable energy difference in the molding process itself resulting from the inclusion of crumb rubber. Hence, this study compares the environmental impacts of crumb rubber production with production of several other conventional plastics and rubber materials:

- Ethylene Propylene Diene Monomer (EPDM) Rubber
- Styrene Butadiene Rubber (SBR)
- High Density Polyethylene (HDPE)
- Low Density Polyethylene (LDPE)

Since the molded crumb rubber substitutes for the same amount of traditional materials, emissions associated with transportation were assumed to be similar and ignored in the analysis. The size of the crumb rubber used in molded products is the same as that used in asphalt production.

Artificial turf production

In artificial turf production, cryogenically produced crumb rubber or EPDM rubber is mixed with sand using blending equipment on site. The process flow for cryogenic crumb rubber production is shown in Fig. 8. The size of the crumb rubber varies from 10 to 30 mesh. Crumb rubber is preferred over EPDM rubber as a cost-effective alternative with superior performance. In this study, the production of cryogenic crumb rubber is compared to the production of EPDM rubber. Process emissions from artificial turf production were assumed to be identical for the base and alternative case, and hence not considered in this study.

Tire retreading

Conventional retreading involves precured tread production using a mix of synthetic rubber, carbon black, and natural rubber. Crumb rubber can be used as a replacement for synthetic rubber such as SBR. The average quantity of crumb rubber used is 10% of the total synthetic rubber. It is assumed that the quantities of other raw materials and

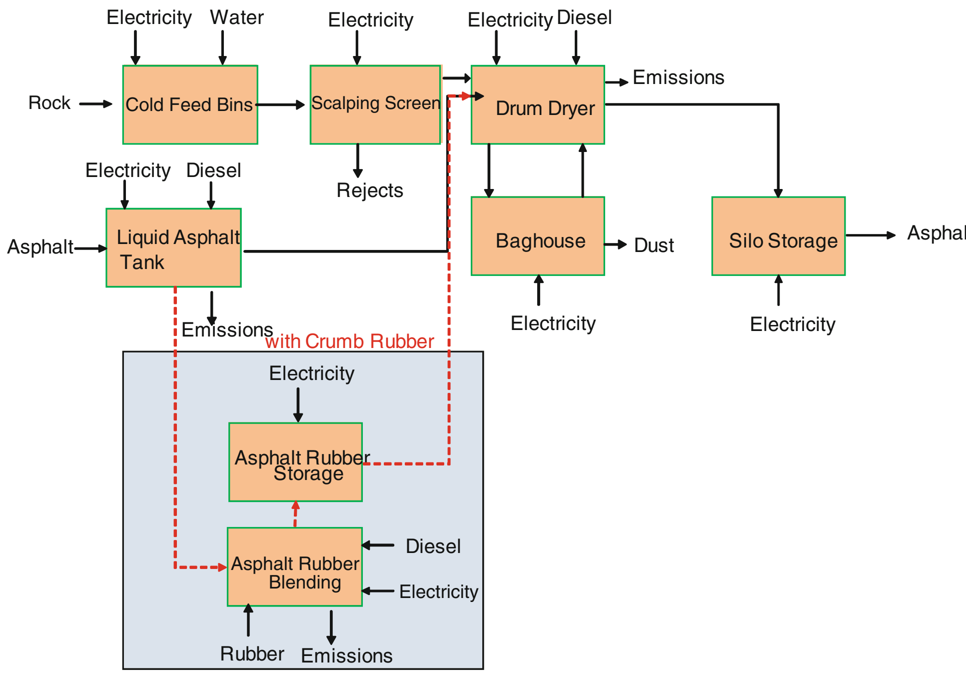


Fig. 7 System boundary for asphalt manufacturing

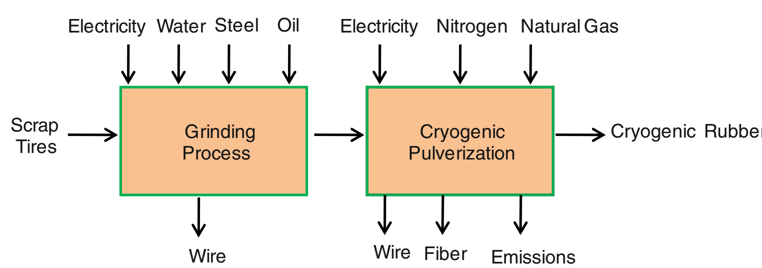


Fig. 8 Cryogenic pulverization process flow

energy consumption during the pre-cured tread production process remain the same. The process flow of retreading is shown in Fig. 9.

Summary of life cycle inventory results

The following is a summary of emission reductions for various scrap tire applications, focusing on air pollutants and solid waste. Resource use and emissions to water and soil are not discussed here, but are included in the LCIA. Figures 10, 11, 12, 13, and 14 show the relative differences in air emissions between the base cases and alternative cases. A positive value of this difference indicates that there is an improvement when moving from the base case (no scrap tires) to the alternative. In the case of the boiler, the improvement is calculated as the emissions avoided from the reduction in the use of coal. In the case of the waste-to-energy plant, the data were directly available as the difference between the base case and the alternative.

In Figs. 12 and 13 the sensitivity of air emissions to variations in cement production methods is indicated by error bars in the column for cement plants. Such data were unavailable for other processes.

Greenhouse gas emissions

From Fig. 10, it is evident that scrap tire applications in cement plants, incinerators, and artificial turf appear to offer reductions of GHG emissions. The use of scrap tires for asphalt production leads to an increase in GHG emissions because asphalt production using crumb rubber from scrap tires involves additional processing steps that require inputs such as electricity and diesel.

As seen from Fig. 10, scrap tire use in cement plants can reduce GHG emissions by 543 kg (CO_2 eq.) per MT. If one accounts for the fact that about 27% of CO_2 emissions from scrap tire combustion come from renewable biomass (natural rubber), then an additional CO_2 credit can be deducted from total emissions. Similar deductions can be made for the boiler and incinerator. When deductible CO_2

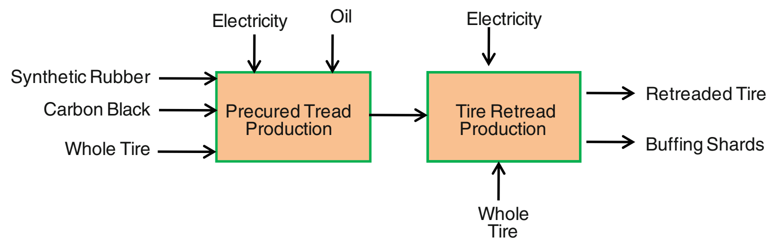


Fig. 9 Tire retreading process flow

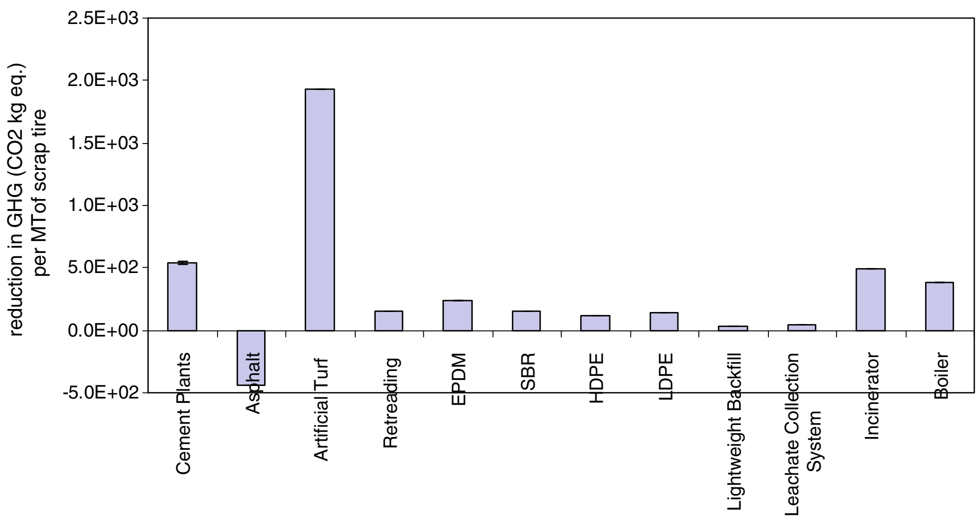


Fig. 10 GHG emission reductions for scrap tire applications

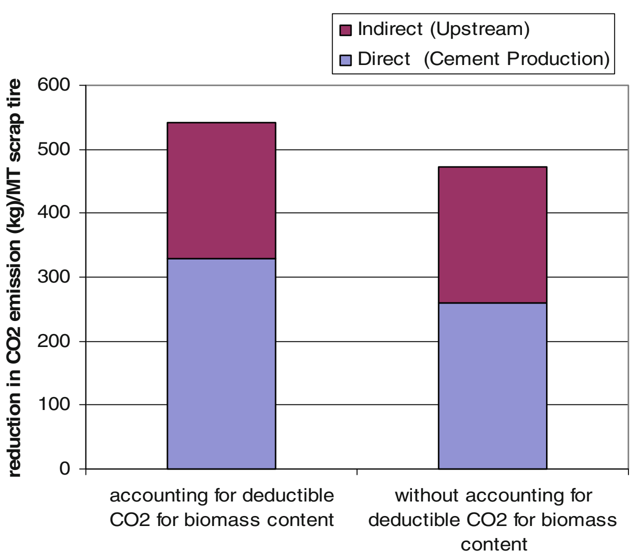


Fig. 11 Reductions in direct and indirect CO_2 emissions per MT of scrap tires

is taken into account, the total GHG emission reduction would be 613 (kg CO_2 eq.) for cement plants.

The largest contributor to GHG emissions is CO_2. Hence, reductions of CO_2 in the supply chain (indirect emissions) and cement production (direct emissions) were estimated for a cement plant to identify the phase where the largest reduction occurs. Indirect emissions refer to emissions associated with upstream processes such as coal and lime mining whereas direct emissions refer to emissions from combustion of fossil fuels in a cement plant. Figure 11 shows that CO_2 emission reduction is larger in cement production when scrap tires are used along with coal. This is because scrap tires release less CO_2 per Joule of energy delivered than coal. The reduction in upstream CO_2 emission is due mainly to avoided coal mining.

If it is assumed that scrap tires will be landfilled in the absence of alternative applications, then this would actually increase GHG emissions by 33 kg (CO_2 eq.) per MT of scrap tires as compared to leaving scrap tires abandoned (ICF 2006).

Criteria air pollutants

Figure 12 shows that the utilization of scrap tires in cement plants and artificial turf results in large reductions of criteria air pollutants and volatile organic carbons (VOCs). Criteria air pollutants refer to six common air pollutants that include ground-level ozone, particulate matter, nitrogen oxides (NO_x), sulfur oxides (SO_x), carbon monoxide, and lead. They are called criteria pollutants because the US EPA has established their permissible ambient air concentrations based on human health and environmental criteria. Since criteria air pollutants and CO_2 emissions are largely due to combustion of fossil fuels, it is no surprise

Fig. 12 Emission reductions of common air pollutants per MT of scrap tires. *Note*: Error bars represent the range obtained from sensitivity analysis for cement plants

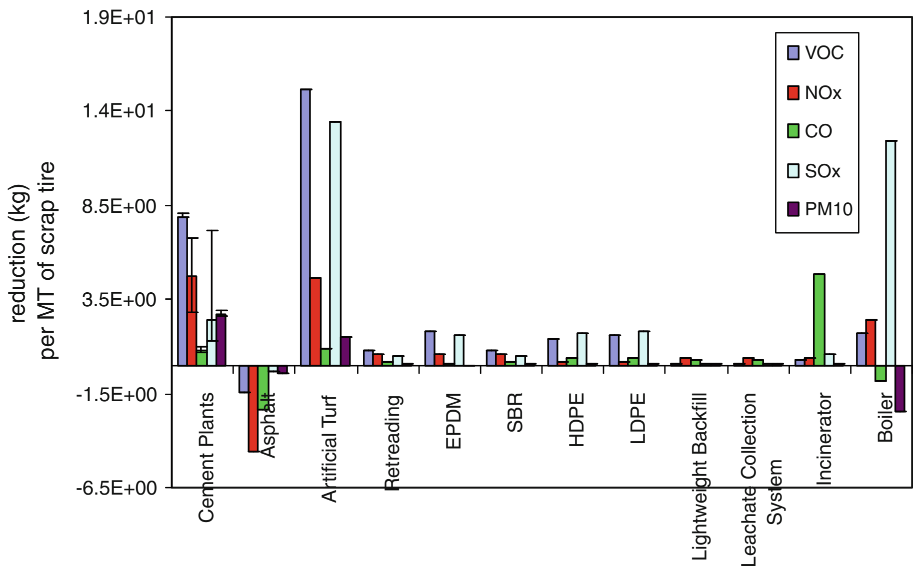


Fig. 13 Dioxin emission reductions per MT of scrap tires. *Note*: Error bars represent the range obtained from sensitivity analysis for cement plants

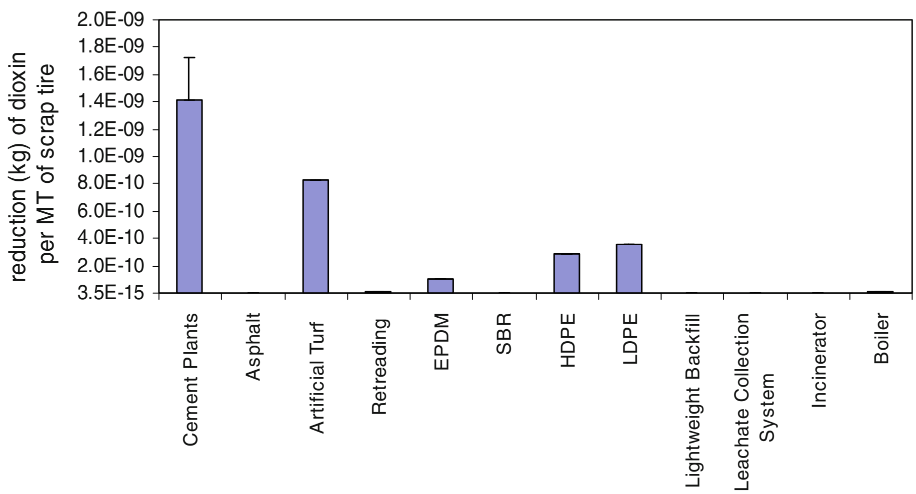
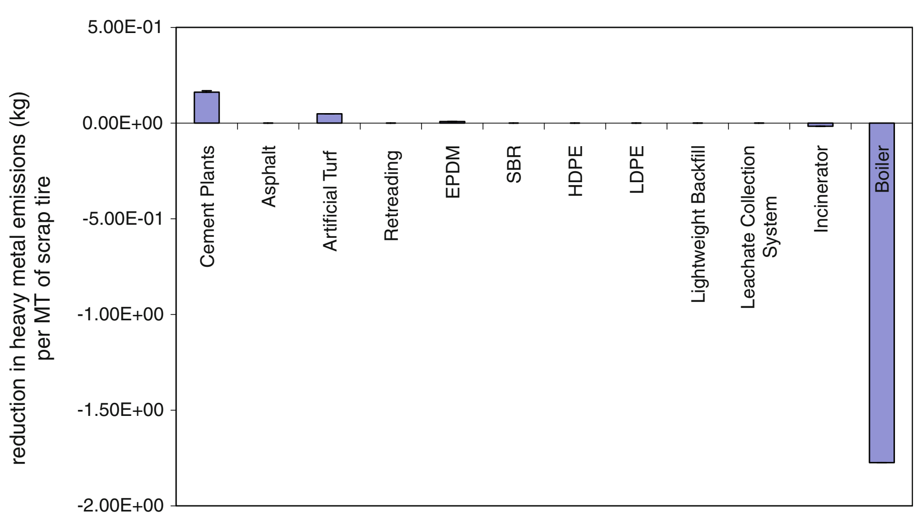


Fig. 14 Heavy metal emission reductions per MT of scrap tires



that CO_2 emissions are correlated with emissions of criteria pollutants. Again, application of scrap tires in asphalt production increases the emissions of NO_x, SO_x, CO, and PM10 over the base case. A significant variation is found in the estimates of NO_x and SO_x reductions in the case of cement plants, as evidenced by large error bars obtained from sensitivity analysis (see Fig. 12).

Dioxins

Figure 13 shows estimated reductions in dioxin emissions from various scrap tire applications. Dioxin refers to a group of chemicals that have a similar chemical structure and mode of toxic action, and are likely human carcinogens. The group consists of polychlorinated dibenzo-dioxins (PCDDs), polychlorinated dibenzo-furans (PCDFs), and polychlorinated biphenyls (PCBs). Dioxins are released in trace quantities during combustion, chlorine bleaching, and manufacturing; they are persistent and can bio-accumulate. As with GHG emissions, scrap tire use for both artificial turf and cement plants offers reductions in dioxin emissions. It should be noted that these reductions do not take into account the process level emissions of dioxin from scrap tire use in incinerators due to lack of data, and inclusion of those data might change the relative benefits. As shown in Fig. 13, some reduction of dioxin emissions may be achieved by substituting molded crumb rubber for EPDM, HDPE, and LDPE.

Heavy metals

In the case of heavy metal emissions, substitution of scrap tires for coal and petcoke in cement plants offers the largest reduction benefits (see Fig. 14). The second largest reduction benefits are obtained from scrap tire application in artificial turf. In contrast, the use of scrap tires in a boiler increases heavy metal emissions significantly, mostly due to higher airborne emissions of metals relative to the use of coal (Reisman 1997). The difference in heavy metal emissions between scrap tire applications in cement plants and boilers may be attributed to variations in process materials and composition of coal used. The heavy metal emissions included in the study are vanadium, nickel, copper, zinc, aluminum, mercury, arsenic, tin, thallium, barium, selenium, cobalt, antimony, manganese, selenium, lead, cadmium, and molybdenum. It should be noted that heavy metal emissions data from cement plant operations are neither complete nor precise.

Solid waste

As shown in Fig. 15, solid waste releases may increase when scrap tires are utilized for civil engineering applications and molded product substitutions. Since solid waste information is either limited or not available for molded products (e.g., EPDM), the increases may be due to data gaps. Unlike other emissions, solid waste generation may increase for artificial turf production when scrap tires are utilized. Using scrap tires for energy use in cement plants, boilers, and incinerators may reduce solid waste production. For cement plants and boilers, the decline is attributed to less utilization of coal and petcoke. Coal mining produces significant amounts of solid waste. The reason for large discrepancies between boilers and cement plants the lack of data on solid waste produced in hard coal mining. Hard coal is used in cement plants along with petcoke, whereas the boiler uses generic coal for which solid waste data are available. With respect to the incinerator, the reduction in solid waste can be attributed to steel produced as a byproduct from scrap tire use, which avoids the solid waste produced in steel manufacturing. Note that the solid waste reductions discussed here refer to indirect solid waste releases associated with upstream processes. Inclusion of direct solid waste generation, such as ash from boilers, may alter the results.

Life cycle impact assessment results

The potential consequences of environmental emissions include a variety of human and ecological impacts such as loss in biodiversity, wildlife habitat degradation, and chronic human illnesses. In this section, overall impact potentials are assessed for the substitution of scrap tires in place of traditional materials. The impacts are measured using midpoint indicators, which quantify the potential for causing harm in each impact category rather than predicting the actual consequences. Confidence bars for some impact assessment results are larger than others due to variability in the LCI results in the "Summary of life cycle inventory results" section.

Since the primary objective is to measure relative improvements in environmental performance, differences are calculated between the impact potentials of the base cases and those of alternative cases. The premise is that if a reduction in impact potential is positive, then scrap tire substitution may lead to overall reduction in adverse impacts. Even if the magnitude of the impact potential is small for each individual case, it is beneficial to have an alternative with a net positive impact reduction because actual environmental impacts often result from the cumulative effects of thousands of industrial processes.

Global warming is exacerbated by emissions of greenhouse gases such as carbon dioxide, methane, and NO_x. Except for asphalt, all the scrap tire applications considered

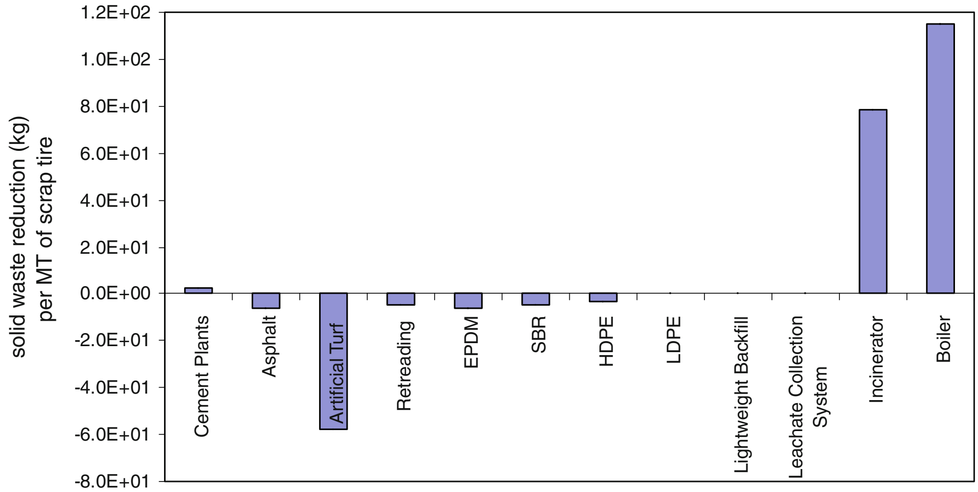


Fig. 15 Solid waste reductions per MT of scrap tires

offer positive reductions in global warming potential (see Fig. 10). Artificial turf, cement plants and incinerators represent the top three opportunities for scrap tire applications to reduce global warming. These results do not take into account deductible CO_2 due to the presence of natural rubber in scrap tires. Accounting for deductible CO_2 would lower global warming potential by 70 kg CO_2 eq. each for the cement plants and incinerator, and 31 kg CO_2 eq. for the boiler per MT o f scrap tires. The difference in cement plants and the boiler is attributed to a smaller fraction of scrap tires being used in the boiler.

Acidification is a consequence of emissions of sulfur oxides (SO_x) and nitrogen oxides (NO_x). Reductions in SO_x and NO_x for scrap tire application in artificial turf, cement plants, and boiler are larger, resulting in significant reductions in acidification potential. With respect to asphalt production, the substitution of scrap tires causes a net increase in acidification potential due to an increase in SO_x and NO_x emissions (see Fig. 16). As described earlier, this increase is a result of scrap tire application in asphalt production requiring an additional processing step, with an associated increase in fossil fuel consumption. A significant uncertainty exists for acidification potential from cement plants due to large variations in NO_x and SO_x emissions.

Ecotoxicity is mainly caused by heavy metals such as mercury, cadmium, zinc, and vanadium in air and water; and chloride and benzopyrene in water. As shown in Fig. 17, unlike acidification and other impact categories, scrap tire utilization in cement plants and boilers offers relatively small reductions in ecotoxicity potential. In fact, utilization of scrap tires in incinerators may increase ecotoxicity due to an increase in chloride emissions in water contributed by the use of soda. As in the case of acidification, scrap tire utilization in artificial turf provides a large reduction in terms of ecotoxicity potential.

Eutrophication results from emissions of nitrogen oxides, ammonia and phosphorus. As seen in Fig. 18, eutrophication potential is reduced by using scrap tires in cement plants, artificial turf, incinerators, and boilers. Sensitivity analysis reveals that reduction in eutrophication can vary appreciably depending upon the methods of cement production. Substitution of crumb rubber derived from scrap tires for SBR, EPDM, HDPE, and LDPE provides small but positive reductions in terms of eutrophication potential.

In the case of cement plants, human carcinogenic potential is primarily contributed by soil emissions in the form of arsenic, the main source of which is coal mining. Since scrap tires replace coal in cement plants, this leads to a decrease in arsenic emissions thereby reducing human carcinogenic potential. In the case of artificial turf, the major contribution is via waterborne emissions in the form of chloride. Since utilization of scrap tires in artificial turf reduces chloride emissions, it results in a larger reduction in human cancer potential (see Fig. 19). Use of scrap tires in both asphalt and incinerators leads to an increase in chloride emissions in water. This is the reason that scrap tire use in asphalt production and incineration increases human cancer potential. For the boiler, the increase in human cancer potential from scrap tire utilization is due to an increase in airborne emissions of arsenic.

The major contributors to human health non-cancer potential are lead, cadmium, mercury, and thallium as air emissions; chloride and lead as water emissions; and lead, arsenic, and barium as soil emissions. Cement plants offer a significant improvement in this impact category, mainly because of the reduction in lead as air emissions from scrap tire use (see Fig. 20). For incinerators and boilers, increases in human non-cancer potential from scrap tire use are due to increased emissions of chloride and lead into the environment. As discussed earlier, the increase in chloride emissions is attributed to the use of soda in the incinerator.

Fig. 16 Reduction in TRACI impacts—Acidification. *Note*: Error bars represent the range obtained from sensitivity analysis for cement plants

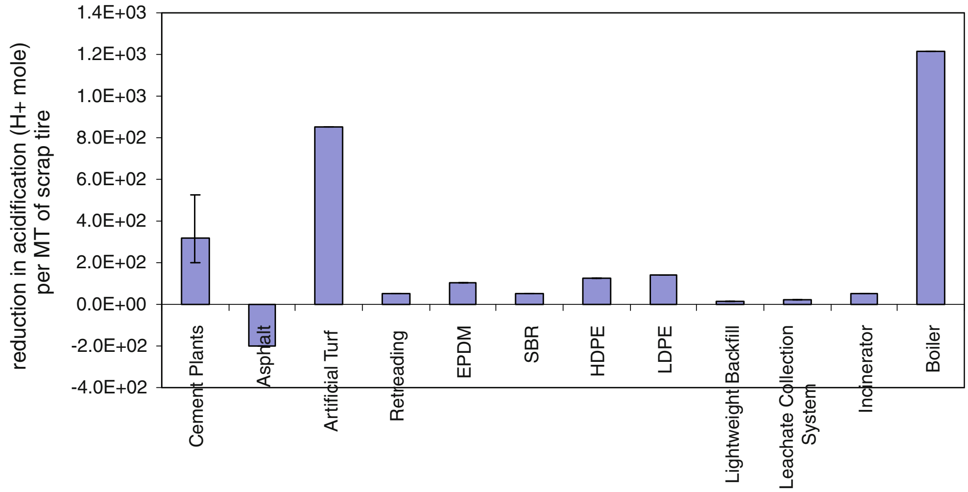


Fig. 17 Reduction in TRACI impacts—Ecotoxicity

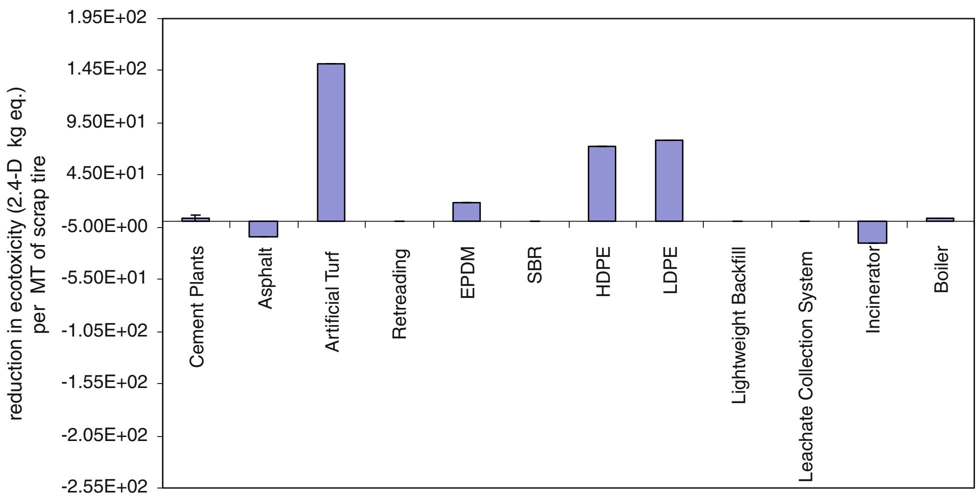
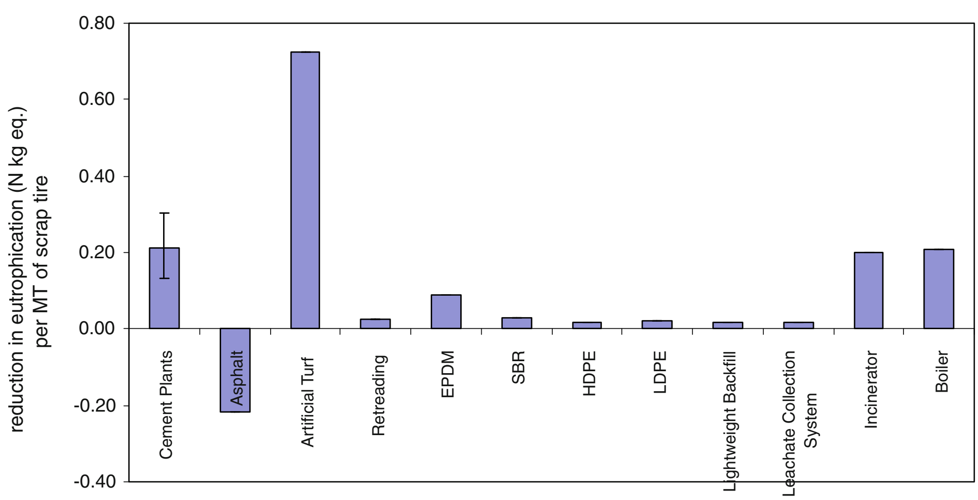


Fig. 18 Reduction in TRACI impacts—Eutrophication. *Note*: Error bars represent the range obtained from sensitivity analysis for cement plants



Human health impacts may result from point source emissions of criteria pollutants. Major criteria pollutants contributing to human health effects are NO_x, SO_x, and particulate matter less than 2 µm. Reductions in human health impact potential associated with scrap tire application in cement plants, artificial turf, and boiler are caused

Fig. 19 Reduction in TRACI impacts—Human health cancer

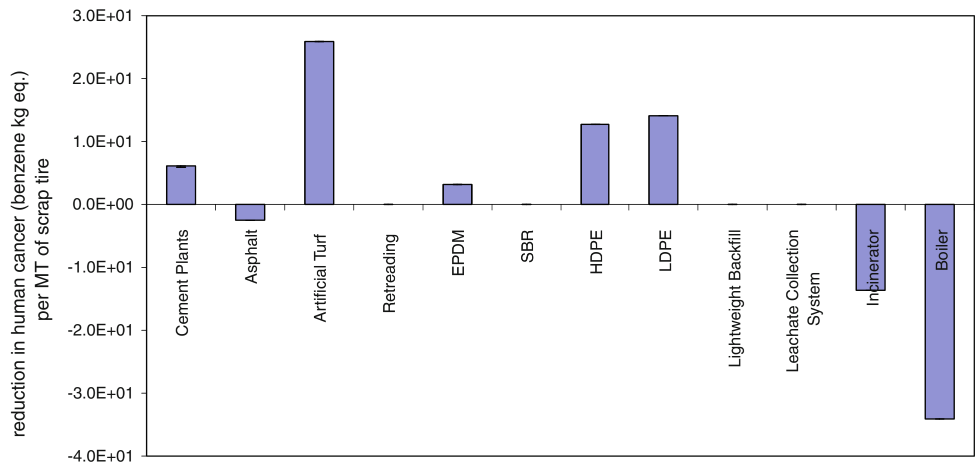
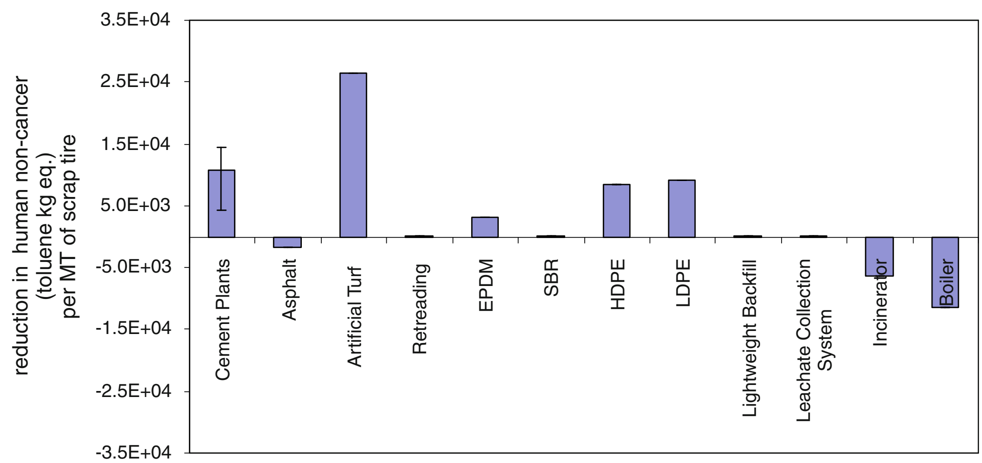


Fig. 20 Reduction in TRACI Impacts—Human health and Noncancer. *Note*: Error bars represent the range obtained from sensitivity analysis for cement plants



by reductions in SO_x and NO_x emissions (see Fig. 21). Since high variability exists in SO_x and NO_x emissions for cement plants, this leads to a larger variability in reduction on human health criteria.

Photochemical smog is caused by the interaction between sunlight and chemicals such as NO_x, and VOCs. Photochemical smog, consisting of ozone, particulates, NO_x, and unreacted hydrocarbons, can cause eye irritation and respiratory diseases. Since scrap tire utilization in cement plants, artificial turf, and the boiler significantly lowers emissions of NO_x and VOCs, this translates into reduction of photochemical smog formation potential (see Fig. 22).

Emissions of ozone depleting substances such as chlorofluorocarbons (CFCs) and bromofluorocarbons are responsible for the destruction of the ozone layer. They catalyze the breakdown of ozone by releasing chorine and bromine radicals. Emissions of ozone-depleting substances by various applications are negligible; hence the prospect of reducing ozone depletion from scrap tire utilization is small. Nonetheless, artificial turf and EPDM offer the largest opportunities for reduction of ozone depletion potential due to scrap tire utilization (Fig. 23).

Discussion and conclusions

This study investigates the uses of scrap tires as tire-derived fuel (TDF), as shredded tires in civil engineering applications, and as crumb rubber in various products. The TDF applications investigated include cement production, boilers, and waste-to-energy incinerators. Civil engineering applications studied include lightweight backfill and leachate collection systems. Crumb rubber applications include artificial turf production, molded products manufacturing, asphalt production, and tire retreading.

In terms of LCI, the use of scrap tires results in reductions in GHG emissions for all of the applications considered except for asphalt production. The increase in GHG emissions for asphalt may be due to an additional step requiring processing of crumb rubber which entails more

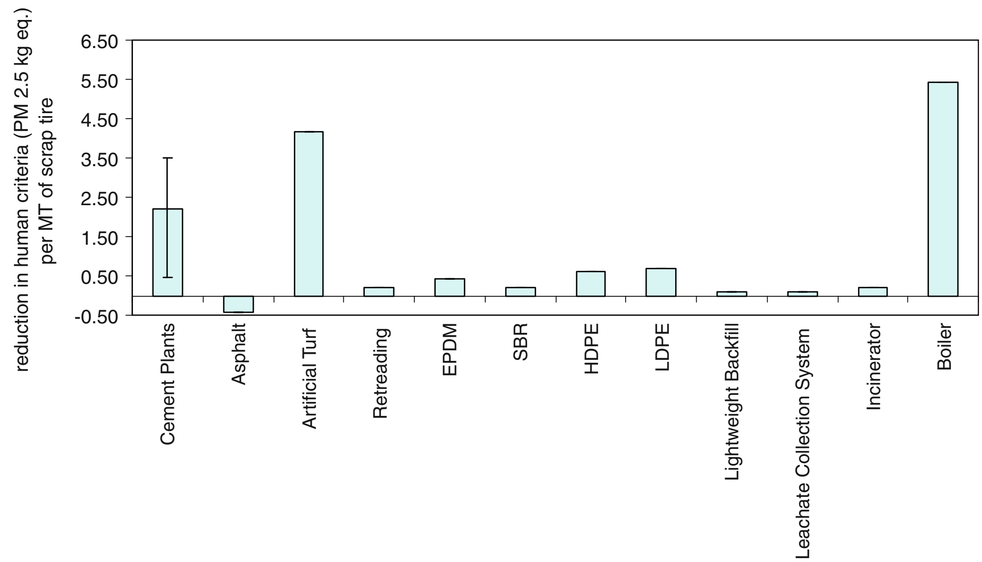


Fig. 21 Reduction in TRACI impacts—Human health criteria and Point source. *Note*: Error bars represent the range obtained from sensitivity analysis for cement plants

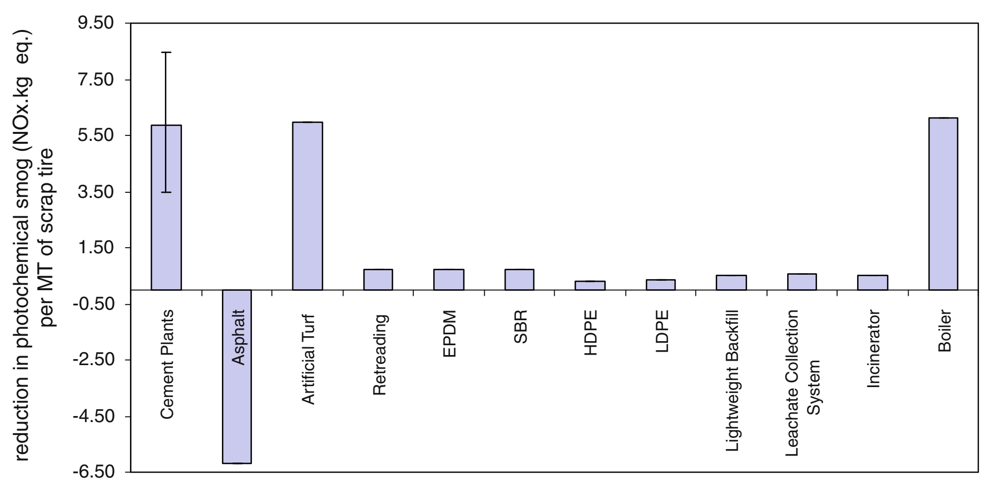


Fig. 22 Reduction in TRACI impacts—Photochemical smog. *Note*: Error bars represent the range obtained from sensitivity analysis for cement plants

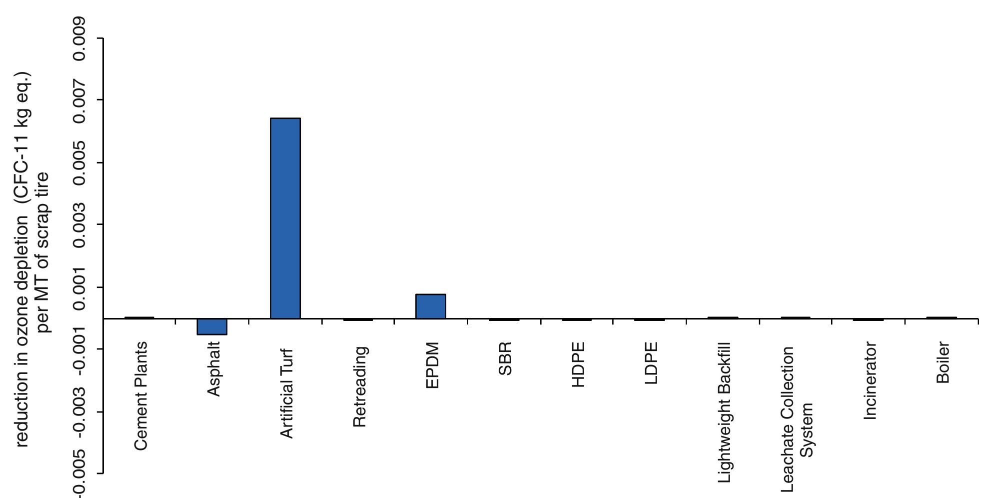


Fig. 23 Reduction in TRACI impacts—Ozone depletion

fossil fuel consumption. Cement manufacturing and artificial turf production provides the greatest reductions in GHG emissions. For example, every metric ton of TDF substituted for coal in cement kilns avoids an estimated 543 kg (CO_2 eq.) of GHG emissions (613 kg when renewable biomass CO_2 is taken into account) whereas disposal of scrap tires in landfills increases GHG emissions by 33 kg (CO_2 eq.) per metric ton disposal. In most of the airborne emissions studied, the scrap tire application offering the largest reductions is artificial turf, followed by cement plants. Utilization of scrap tires in cement plants reduces heavy metal emissions, criteria air pollutants, dioxin, and solid wastes. In contrast, application in asphalt production increases GHG, criteria pollutant and dioxin emissions, and solid waste generation. For the remaining applications, reductions in environmental burdens can be seen in most categories and increases in a few categories. For example, use of ground rubber for molded products increases solid waste generation, mainly due to increased solid waste generation in the supply chain.

TRACI impact analysis enables aggregation of emissions by impact categories to calculate the overall impact potentials of alternative scenarios. Inventory analysis along with LCIA can inform decision makers about the benefits of scrap tire utilization relative to traditional material uses, and help identify the possible opportunities for environmental improvements. Since there is a direct correlation between the magnitude of emissions and their impact potentials, alternative pathways that reduce individual emissions will tend to reduce impact potentials. Therefore, in most cases the utilization of scrap tires in artificial turf and cement plants offers the greatest reductions in environmental impact potential. One exception is ecotoxicity potential, where there is minimal benefit from utilizing scrap tires in cement plants.

In conclusion, scrap tire utilization is environmentally preferable, since stockpiling of scrap tires creates fire and human health hazards while disposal of scrap tires in landfills may disturb landfill integrity. As discussed earlier, the use of ground rubber in artificial turf provides the greatest improvements in most TRACI impact categories, because it avoids significant emissions from synthetic rubber. However, the market for ground rubber in artificial turf is already 100% saturated. The market for scrap tires is predominantly for energy as TDF in cement plants, power plants, and incinerators, which accounts for 50% of the total scrap tire market. In 2005, nearly 155 million tires were used as TDF whereas only 37.5 million tires were used in the entire ground rubber market, out of which 35% went to producing athletic surfaces. Based on the LCA results, the use of shredded tires as TDF in cement plants appears to be a viable option for increasing scrap tire utilization and realizing environmental benefits.

Acknowledgments This LCA study was commissioned by Holcim, a worldwide cement company that has embraced the practice of industrial ecology including the use of tire-derived fuel. Holcim provided primary data for characterization of cement production processes. At Holcim's request, The Ohio State University has conducted the study in an independent and unbiased manner.

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