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Qualitative Lifecycle Analysis of Rail Tie Materials

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14. ABSTRACT
To address the large environmental impact of the transportation sector, opportunities for mitigating greenhouse gas (GHG) emissions must be identified. After direct emissions from locomotives, rail ties are the second largest source of lifecycle railway GHG emissions. To better understand these impacts, this research qualitatively evaluated the environmental impacts, benefits, and drawbacks of four rail tie materials: timber, concrete, steel, and plastic composite. The manufacture, operation, and disposal stages of the rail tie lifecycle were considered. There was no strong consensus among the existing literature about the absolute lifecycle GHG emissions for each rail tie material, as each study had a unique set of assumptions that led to different ranges. However, there was a consensus that concrete rail ties had the lowest lifecycle GHG emissions, followed by timber. Despite the seemingly lower environmental impact, with concrete rail ties having the highest upfront financial cost their market penetration has stayed well below that of timber. Steel and composite rail ties can be recycled after disposal but have structural qualities that prevent these two materials from penetrating the market. Studies that have considered stored carbon and sustainable forestry practices in their lifecycle analyses of timber rail ties have indicated that timber rail ties might have the lowest lifecycle emissions, but more research in this area is needed.

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METRIC/ENGLISH CONVERSION FACTORS

ENGLISH TO METRIC

LENGTH (APPROXIMATE)

1 inch (in)	=	2.5 centimeters (cm)
1 foot (ft)	=	30 centimeters (cm)
1 yard (yd)	=	0.9 meter (m)
1 mile (mi)	=	1.6 kilometers (km)

AREA (APPROXIMATE)

1 square inch (sq in, in^2)	=	6.5 square centimeters (cm^2)
1 square foot (sq ft, ft^2)	=	0.09 square meter (m^2)
1 square yard (sq yd, yd^2)	=	0.8 square meter (m^2)
1 square mile (sq mi, mi^2)	=	2.6 square kilometers (km^2)
1 acre = 0.4 hectare (he)	=	4,000 square meters (m^2)

MASS - WEIGHT (APPROXIMATE)

1 ounce (oz)	=	28 grams (gm)
1 pound (lb)	=	0.45 kilogram (kg)
1 short ton = 2,000 pounds (lb)	=	0.9 tonne (t)

VOLUME (APPROXIMATE)

1 teaspoon (tsp)	=	5 milliliters (ml)
1 tablespoon (tbsp)	=	15 milliliters (ml)
1 fluid ounce (fl oz)	=	30 milliliters (ml)
1 cup (c)	=	0.24 liter (l)
1 pint (pt)	=	0.47 liter (l)
1 quart (qt)	=	0.96 liter (l)
1 gallon (gal)	=	3.8 liters (l)
1 cubic foot (cu ft, ft^3)	=	0.03 cubic meter (m^3)
1 cubic yard (cu yd, yd^3)	=	0.76 cubic meter (m^3)

TEMPERATURE (EXACT)

[(x-32)(5/9)] °F = y °C

METRIC TO ENGLISH

LENGTH (APPROXIMATE)

1 millimeter (mm)	=	0.04 inch (in)
1 centimeter (cm)	=	0.4 inch (in)
1 meter (m)	=	3.3 feet (ft)
1 meter (m)	=	1.1 yards (yd)
1 kilometer (km)	=	0.6 mile (mi)

AREA (APPROXIMATE)

1 square centimeter (cm^2)	=	0.16 square inch (sq in, in^2)
1 square meter (m^2)	=	1.2 square yards (sq yd, yd^2)
1 square kilometer (km^2)	=	0.4 square mile (sq mi, mi^2)
10,000 square meters (m^2)	=	1 hectare (ha) = 2.5 acres

MASS - WEIGHT (APPROXIMATE)

1 gram (gm)	=	0.036 ounce (oz)
1 kilogram (kg)	=	2.2 pounds (lb)
1 tonne (t)	=	1,000 kilograms (kg)
	=	1.1 short tons

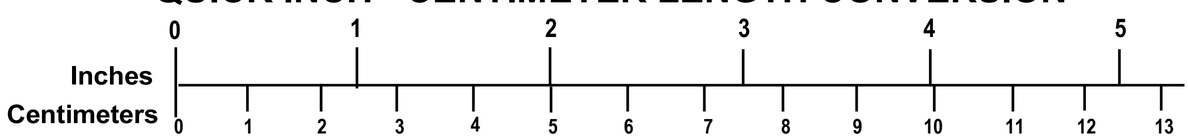
VOLUME (APPROXIMATE)

1 milliliter (ml)	=	0.03 fluid ounce (fl oz)
1 liter (l)	=	2.1 pints (pt)
1 liter (l)	=	1.06 quarts (qt)
1 liter (l)	=	0.26 gallon (gal)
1 cubic meter (m^3)	=	36 cubic feet (cu ft, ft^3)
1 cubic meter (m^3)	=	1.3 cubic yards (cu yd, yd^3)

TEMPERATURE (EXACT)

[(9/5) y + 32] °C = x °F

QUICK INCH - CENTIMETER LENGTH CONVERSION



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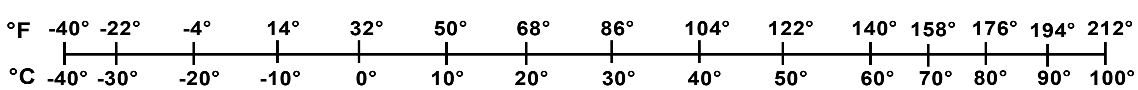

For more exact and/or other conversion factors, see NIST Miscellaneous Publication 286, Units of Weights and Measures. Price $2.50 SD Catalog No. C13 10286

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Contents

Illustrations

Tables

Executive Summary

Rail ties contribute a substantial amount of greenhouse gas (GHG) emissions throughout their lifecycle, from initial production to disposal. The degree of impact varies depending on the material composition of the rail tie because each material has different properties, capabilities, and maintenance requirements. To address the large impact that the transportation sector has on the environment, existing emissions, ecological impacts, and opportunities for environmental improvements must be identified and understood. This report synthesizes information from prior studies and reports with a focus on the environmental impacts, benefits, and drawbacks of the most commonly used rail tie materials: timber, concrete, steel, and composite. Notably, this report does not present a quantifiable range of lifecycle GHG emissions for each material due to differences in assumptions in the existing literature, differences that lead to a large range of outcomes. The authors offer lifecycle analysis and discussion in this report through a qualitative lens; more research is needed to understand relative environmental costs associated with each material.

The lifecycle of a rail tie involves a production and manufacturing stage, a service life and operational stage, and an end-of-life or disposal stage. Although concrete rail ties have the highest upfront cost, they generally have the lowest lifecycle GHG emissions among the examined materials. The greatest source of emissions for concrete rail ties comes from the manufacturing and production stages. Meanwhile, timber rail ties are often the lowest cost option, but have greater lifecycle emissions than concrete rail ties due to disposal methods that release carbon. While timber stores carbon as it grows and therefore reduces the amount of carbon in the atmosphere, stored carbon is released through the disposal process when timber rail ties are sent to the landfill, burned for fuel, or reused. Steel and composite rail ties can be recycled and reused after disposal but have structural qualities that prevent these two materials from being competitive with timber or concrete rail ties in terms of production and cost. This report presents a lifecycle analysis of each rail tie material and discusses opportunities for environmental improvements in the transportation sector related to rail tie materials. With no strong consensus in the existing literature on the absolute GHG emissions of each material, results are presented qualitatively.

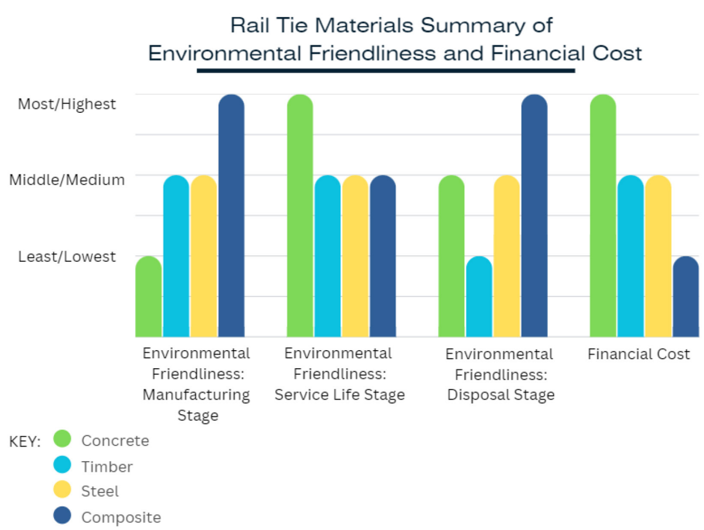


Figure 1. Summary of qualitative environmental and financial costs for each rail tie material.

1. Introduction

The transportation sector is one of the largest emitters of greenhouse gases (GHG) and is responsible for approximately one-third of the nation's GHG emissions (Department of Energy, 2023). To address the growing climate crisis attributed to GHG emissions, the United States is striving to meet a net-zero emissions goal by 2050 (Department of Energy, 2023). Due to the United States' dependence on fossil fuels, certain sectors of the transportation industry, such as rail and aviation, are challenging to decarbonize (Speizer et al., 2024). Further, while direct carbon dioxide (CO_2) emissions from locomotive operations is well understood, research is still emerging to identify *embodied emissions* of rail infrastructure and equipment—GHG emissions associated with up- and down-stream lifecycle stages of these materials (extraction, production, transport, manufacturing, and disposal/end-of-life handling). For example, rail ties can be responsible for large amounts of GHG emissions over the course of their lifecycle (de Andrade and D'Agosto, 2016). There are approximately 207,000 miles of rail track in the United States requiring about 620 million rail ties (mostly timber), of which 23 million are replaced every year (Smith, 2019). Therefore, understanding and reducing the environmental impacts of rail ties is particularly important for decarbonization of the rail sector.

This report sources and synthesizes information from other reports and studies on the lifecycle analysis of concrete, timber, steel, and composite rail ties. In this report, the lifecycle of rail tie materials is considered the raw material extraction and manufacturing of the rail tie components, transportation of the finished tie to the track site, construction and use of the track beds, and disposal of the rail ties. These aspects of rail tie lifecycle were reviewed, and where data was available in the literature, are detailed in the following sections of this report by material type. Absolute GHG emissions for each rail tie material are not disclosed in this report due to the different assumptions used within the existing literature.

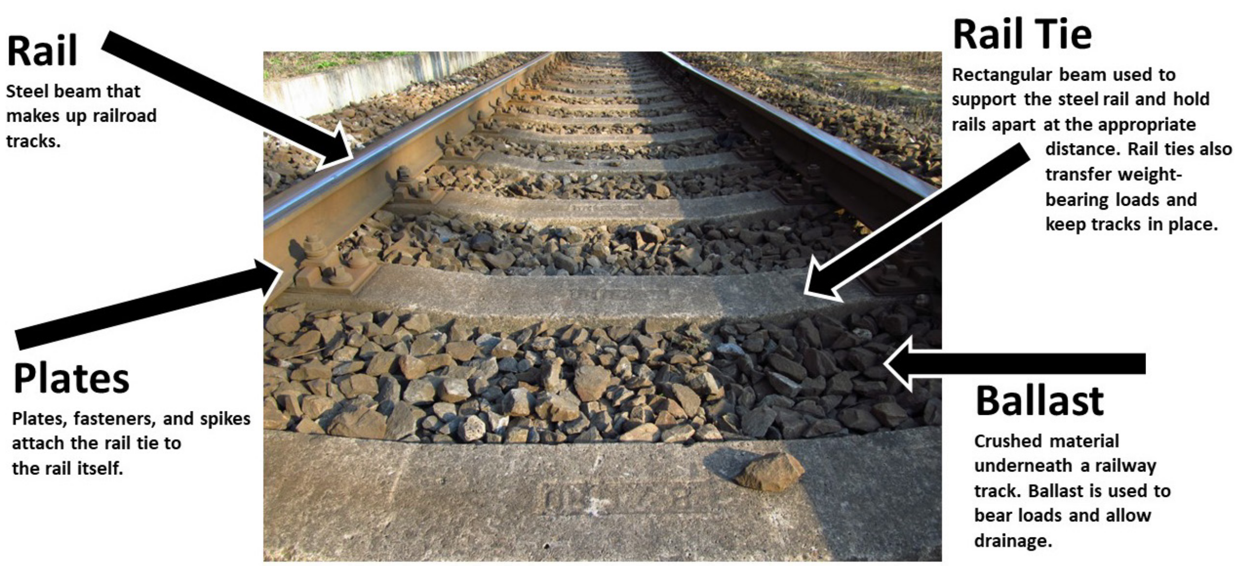
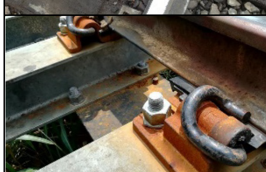
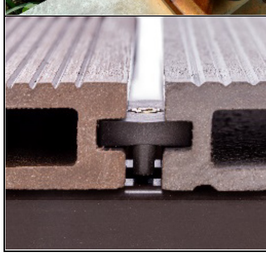


Figure 2. Diagram of railway track components.

A rail tie, also referred to as a *crosstie* or *railway sleeper*, is a rectangular beam used to support the steel rail that makes up railroad tracks (Figure 2). Rail ties are positioned perpendicular to the steel rail and help transfer weight-bearing loads and keep tracks in place. The four main types of materials used to produce rail ties are concrete, timber, steel, and engineered polymer composite. Timber rail ties have been and continue to be the most used type of rail tie since the birth of the rail industry in the early to mid-1800s. According to a 2019 Association of American Railroads Survey, 94.8 percent of the 15.1 million rail ties purchased in 2017 were timber rail ties (Smith, 2019). Due to declining timber supply in the late 1800s, new materials like steel and concrete were sought out for rail tie manufacturing. However, neither steel nor concrete rail tie use took off due to a niche market; concrete and steel rail ties represented less than 5 percent and 0.3 percent of rail tie purchases in the United States in 2018, respectively, with diminishing shares over time (Smith, 2019). Further, chemically treating wood to increase durability, particularly with creosote, became commercially viable in 1838 and continued to advance until the early 1900s (Bolin and Smith, 2013). Rail ties have since had a long history of improvements and increased durability in the transportation industry. In the early 2000s, engineered polymer composite ties, which are composed primarily of post-consumer recycled plastics, were introduced into the rail tie market and have been used periodically throughout North America (Gao and McHenry, 2021), but still make up only 0.3 percent of all rail ties in use (Smith, 2019).

The four materials reviewed in this report have different properties, benefits, and drawbacks. Table 1 lists the qualitative properties of each rail tie material.

Table 1. Rail tie materials and properties.

IMAGE OF MATERIAL	MATERIAL	BENEFITS	DRAWBACKS
	**Concrete**	• Long service life • Low maintenance costs • Lowest lifecycle emissions[1]	• Heavy • High installation cost
	**Timber**	• Adaptable (i.e., easy to assemble and replace, and can be fitted with different types of track) • Renewable	• Susceptible to decay (e.g., fungal infections) and splitting • High environmental cost and concerns when treated with creosote • Growing disposal concerns
	**Steel**	• Reduced track geometry variation prevents early in-service failure • Low weight and easy to handle	• Not suitable for high-speed rail • Susceptible to corrosion • High electrical conductivity
	**Composite**	• High strength and durability • Similar properties to timber	• Under research and development • Prone to cracking and bending • Issues with thermal stability • High financial cost

[1] As described in Crawford, 2009; Bolin and Smith, 2013; and Rempelos et al., 2020.

Generally, all rail ties undergo three main lifecycle stages: manufacturing, operation or service, and end-of-life. These stages vary by material, as each has different requirements for manufacturing, disposal, and maintenance, in addition to differences in service life. Figure 3 summarizes the different lifecycle stages for each material.

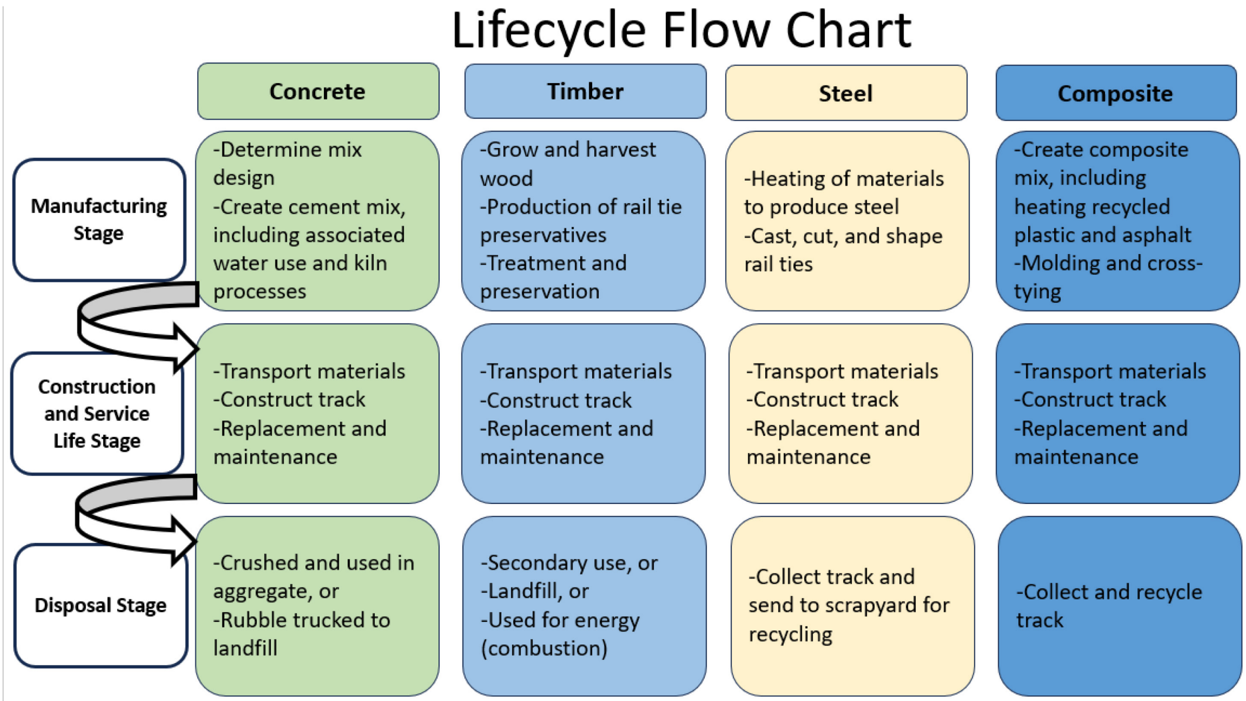


Figure 3. Lifecycle flow chart for concrete, timber, steel, and composite rail ties.

There is some disagreement among researchers regarding which rail tie material yields the highest lifecycle emissions due to variations in assumptions and modeling scenarios, although rail ties made of concrete are generally assumed to have the lowest lifecycle emissions (Crawford, 2009; Bolin and Smith, 2013; Rempelos et al., 2020). Moreover, although numerous papers cite specific numerical values for GHG emissions for different rail tie materials, these values vary significantly across studies due to different assumptions made in each study. Figure 4 identifies general environmental impacts at each stage for concrete, timber, steel, and composite rail ties, although additional research is needed to determine more specific relative environmental costs for each rail tie material.

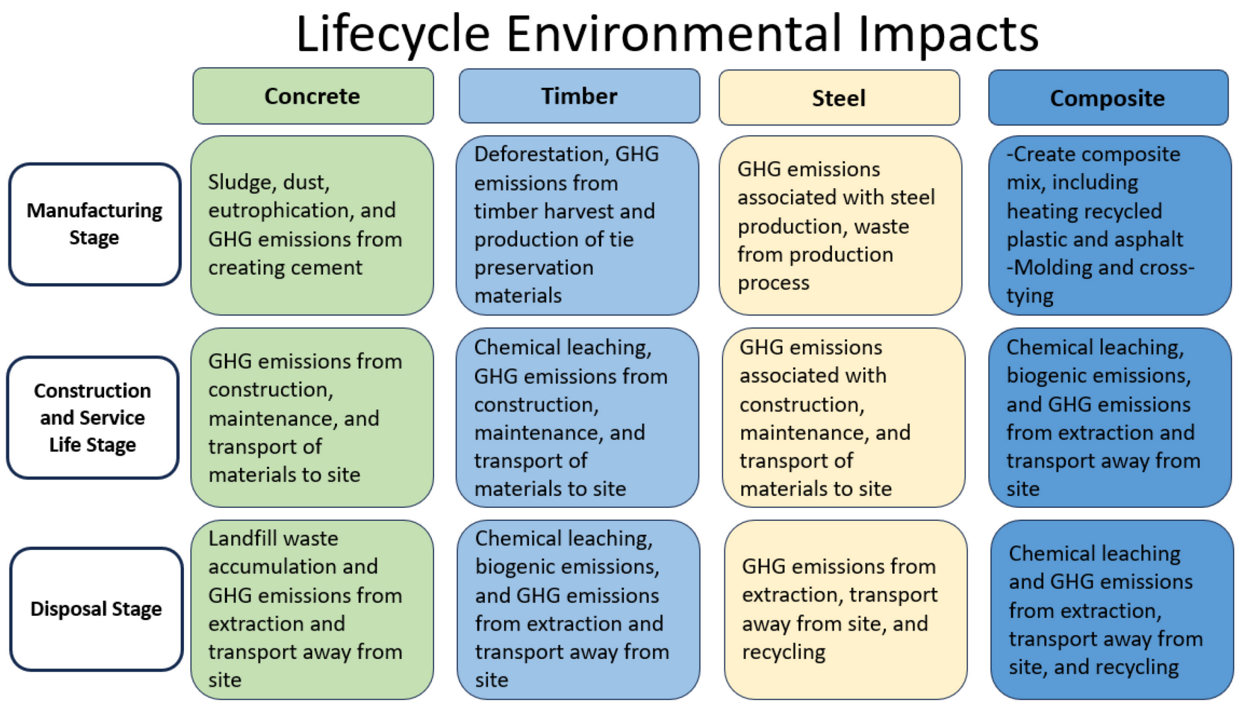


Figure 4. Environmental impacts at each lifecycle stage of concrete, timber, steel, and composite rail ties.

GHG emissions associated with reinforced concrete rail ties have been found to be 59 to 78 percent lower than timber rail ties (Crawford, 2009). Under high traffic conditions, concrete rail ties emit fewer lifecycle GHG emissions compared with timber rail ties, as concrete rail ties are more durable under these conditions and thus require fewer replacements and less maintenance (Rempelos et al., 2020). The disposal process of concrete rail ties has also been found to result in fewer GHG emissions than the disposal process for timber rail ties (Milford and Allwood, 2010).

However, concrete rail ties have a more resource-intensive production process than other rail ties. For example, concrete rail ties have been found to result in 1.8 times more fossil fuel use and 8.7 times more water use than timber rail ties when carbon storage is considered in the lifecycle analysis of timber (Bolin and Smith, 2013).

Lifecycle emissions also depend on the durability of the rail tie, especially under various environmental stressors. Bolin and Smith (2013) found that, after concrete, creosote-treated timber rail ties have a lower carbon emissions impact than those made from other types of treated wood, steel, or composite. Of the treated wood ties, Diaz et al. (2022) found that copper-chrome-arsenic (CCA)-treated timber rail ties had a higher carbon cost compared with copper-boron-arzole-, creosote-, pentachlorophenol-, or furfuryl alcohol-treated timber rail ties. (Refer to Section 3.1 Environmental Impacts of Timber, for additional information on chemically treated timber rail ties.)

Due to an increased interest in reducing GHG emissions the rail industry is shifting away from using timber rail ties. Amtrak plans to replace all aging wood ties with concrete ties along the Northeast Corridor of the United States; these rail ties were last replaced in the 1970s (Lim et al., 2023). In addition to improving environmental sustainability, another primary purpose of this replacement is to improve ride quality, comfort, and increase service reliability (Amtrak, 2024), which are all key issues in passenger rail service, but may not be a priority for freight rail (except for service reliability). It is important to note that these improvements to ride quality, comfort, and service reliability derive from replacing aging infrastructure regardless of the rail tie material. Similarly, Union Pacific has also been replacing their rail tie infrastructure. Specifically, Union Pacific has replaced over three million timber rail ties with composite rail ties (Union Pacific, 2023). These replacements have been prioritized in areas of high heat, humidity, and at subgrade due to increased vulnerability of timber to decay. Union Pacific installed these composite rail ties with the intent of recycling or repurposing them at the end of their lifespan, which is not an option for timber rail ties (Union Pacific, 2023).

It is important to note that the entire footprint of America's track infrastructure also plays a role in relative amounts of GHG emissions and embodied carbon. One study found that a rail network could reduce its CO_2 impact by 40 percent if it were to transition from a conventional track design to a double-headed embedded rail design, an innovation in design that includes a reinforced concrete slab to support the rail section (Milford and Allwood, 2010). The slab provides both vertical and lateral support, which increases the durability of the structure and extends its service life (Milford and Allwood, 2010).

The subsequent sections of this report present data on the lifecycle GHG emissions of each type of rail tie material.

2. Concrete

2.1 Environmental Impacts

A substantial proportion of the lifecycle emissions from concrete rail ties derives from the production and manufacturing stages of the rail tie itself, particularly the cement and steel rebar (Diaz et al., 2022). Concrete production emits large amounts of carbon. The manufacture of cement worldwide accounts for five percent of global GHG emissions due to fossil fuel use during the cement clinker manufacturing process (Diaz et al., 2022). The initial embodied emissions from the production stage of reinforced concrete make up about 29 to 38 percent of the total lifecycle embodied emissions (Crawford, 2009; Bolin and Smith, 2013).

Concrete production and manufacturing can also impact water quality and result in waste. Water use during cement manufacturing leads to wash-out and eutrophication impacts from sludge. *Eutrophication* is the increased concentration of nitrates and phosphates in bodies of water that leads to excessive algae growth, which, in turn, reduces oxygen in the water, harming the ecosystem (Kiani et al., 2008). During cement manufacture, dust is generated from the cement kiln process (grinding and heating). However, these particles are often collected and used later in the production process or other processes and thus contribute minimally to solid waste generation (Kiani et al., 2008).

The service life stage of a concrete rail tie contributes fewer lifecycle GHG emissions than the production stage (Diaz et al., 2022). Concrete rail ties result in fewer GHG emissions than timber during the service life stage because concrete is stiffer and has less rolling resistance than timber. Up to 0.05 gallons of diesel fuel is saved per 1,459 ton-kilometer (1,000 ton-miles) of freight (Bolin and Smith, 2013). Additionally, a small amount of carbon recovery occurs due to the reabsorption of atmospheric CO_2 by the concrete through a naturally occurring process known as *carbon dioxide mineralization* in which CO_2 binds in rocks as a solid mineral (Diaz et al., 2022; Rosa et al., 2022).

Figure 5. Concrete rail tie. Image credit: Adobe Stock.

2.2 Benefits

Concrete rail ties are heavier and stronger than their timber counterparts. An average concrete rail tie weighs approximately 628 pounds, whereas a timber rail tie made from gum wood, a common timber rail tie material, weighs 177 pounds per tie (Crawford, 2009). Concrete rail ties are often used for heavy-haul and high-curvature tracks because their heavier weight and stiffness reduce rail movement (Bolin and Smith, 2013). Concrete rail ties are therefore preferred in areas of high traffic load (Rempelos et al., 2020), and can be used in both freight and passenger rail applications, including high-speed rail.

Concrete rail ties also have a sturdier and steadier line and gauge that reduce the risk of derailment compared with timber rail ties (Manalo et al., 2009), and fewer rail ties are required per length of track. Approximately 1,400 concrete ties are required per kilometer (km) of track, whereas four percent more timber rail ties are required for the same amount of track (Crawford, 2009). Despite a high initial cost, once installed, concrete rail ties have lower maintenance costs because there are fewer ties to maintain (Kiani et al., 2008; Crawford, 2009). Finally, concrete ties typically last longer than timber ties and require fewer replacements than timber ties over their lifetime, allowing for lower lifecycle emissions (Crawford, 2009). End-of-life environmental impacts are minimal as there is no associated chemical leaching or biodegradation leading to toxic waste emissions (Diaz et al., 2022).

In summary, fewer concrete rail ties are needed per track, require less maintenance and replacement, and have a longer service life compared with timber rail ties. These benefits result in fewer lifecycle GHG emissions of concrete rail ties compared with timber rail ties.

2.3 Drawbacks

Although their heavy weight makes concrete rail ties ideal for certain areas, their service life varies. The lifespan of a concrete rail tie depends on rail stress, with projected service life ranging from 20 to 50 years (Crawford, 2009; Bolin and Smith, 2013). Premature failures of concrete rail ties are typically due to cracking and corrosion. Like concrete sidewalks, concrete rail ties experience cracks from repeated stress (Figure 6). In some instances, large batches of installed concrete rail ties had to be replaced within 10 years of their installation (Lim et al., 2023).

Figure 6. An example of cracking in a concrete rail tie.

In addition to cracking and corrosion, other common failures include bond splitting (i.e., internal breakage of concrete tie), shear failure (i.e., soil movement around rail ties due to repeated loading), and surface spalling (i.e., breakage, chipping, flaking, or peeling on concrete surfaces). Concrete rail ties are relatively rigid and inflexible, which leads to a higher load transferred to the rail ties and an associated increase in the risk of deterioration due to flexural cracks (Manalo et al., 2009). Thus, concrete rail ties require additional ballast compared with timber rail tie systems to avoid damage to the rail tie (Manalo et al., 2009; Bolin and Smith, 2013).

Because concrete rail ties are used in heavier operations, they tend to experience failure quicker than other rail tie materials because they undertake a higher bearing pressure. In a scenario where the track system is submerged in water during a flooding event, concrete rail ties may fail to evenly distribute load, requiring the reconstruction of track formation and foundation (Kaewunruen et al., 2018). Similarly, flooding and water can seep through the cracks in concrete rail ties and contribute to the rail tie failure (FRA, 2022). Repeated traffic overloads often lead to subgrade problems, such as progressive shear failure and deformation.

Concrete rail ties are also vulnerable to other impacts. For example, a rail pad that separates the track from the rail tie is susceptible to abrasion that can occur between the track and the top of the rail tie itself (Manalo et al., 2009). Concrete rail ties are also vulnerable to freeze-thaw cycles, where freezing can cause internal pressure and damage when water expands (Riding et al., 2024). However, proper inclusion of air bubbles in concrete mixtures can mitigate the impacts from freezing and thawing because the air bubbles introduce space and relieve pressure.

The cost of concrete ties (upwards of $45 U.S. dollars[2] per tie) is dominated by raw materials (78 percent), with manufacturing overhead (such as capital, insurance, utilities, and wages) comprising only 7 percent of the cost (Lim et al., 2023). The heavy weight of concrete rail ties requires specialized machinery for laying and installation, which can lead to initial costs that are almost double those of timber rail ties (Manalo et al., 2009). Concrete rail ties also require special fasteners and rail pads for electrical and vibration isolation and noise management, which increases their manufacturing costs (Ferdous et al., 2015). All of these factors and special considerations for concrete rail ties contribute to their lifecycle GHG emissions.

Concrete rail ties are not used as widely as timber rail ties and can have poorer durability that leads to higher costs compared with other rail tie materials (Lim et al., 2023). Concrete rail ties were initially adopted due to their marketed durability and low premature failure rate (less than four percent); however, since the 1970s, at least 31 percent of U.S. concrete rail ties have been prematurely replaced due to failures (Lim et al., 2023). If the rail ties do not fail prematurely, the total lifecycle cost of 1 kilometer of track over 100 years is estimated to range from $1 to $1.5 million U.S. dollars[3] (Lim et al., 2023). If the rail ties do fail prematurely, these costs can increase by a factor of 2.7 (Lim et al., 2023). As a whole, the rail industry is not converting to the use of concrete rail ties, although they are used in the expanding high-speed rail sector.

2.4 Disposal

At the end of life, most concrete rail ties (70 percent) are disposed of in landfills (Kiani et al., 2008). Five percent of disposed rail ties are reused by railways and 25 percent are recycled by being crushed and reused as aggregate, although reinforced concrete can be difficult to grind for reuse (Kiani et al., 2008). In some instances, conventional concrete recycling also leads to lower quality recycled aggregate that is less marketable due to challenges with quality control and cost (Tomosawa et al., 2005). With respect to environmental impacts, lifecycle GHG emissions accrue as concrete rail ties are transported from the railway to the disposal site and during the disposal process.

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[2] In 2023 U.S. dollars.
[3] In 2023 U.S. dollars.

3. Timber

3.1 Environmental Impacts

Timber rail ties are primarily made of hardwood species like oak (genus *Quercus*), while approximately eight percent are made of softwood species, primarily Douglas fir (*Pseudotsuga menziesii*) (Smith and Bolin, 2010). Like concrete, the lifecycle of timber rail ties typically includes the manufacturing of the rail ties, transportation to the site, installation, and eventual disposal of the rail ties. GHG emissions associated with manufacturing timber rail ties include those from harvesting, transporting, and milling the lumber (Crawford, 2009). Energy is used during lumber harvesting to run harvesting equipment, transport logs to the mills, and to power equipment for processing and manufacturing. When timber is harvested, leaves and branches are stripped, resulting in sawdust and scrap wood. These by-products are used in other timber products, burned, left on site, or used to feed kilns for drying timber (Crawford, 2009). Other production outputs include waste discharge and particulate emissions, and emissions can lead to acidification, eutrophication, and smog (Bolin and Smith, 2013; Bergman et al., 2014). Other outputs are emitted in the forms of solid waste, wastewater discharge, and chemical releases from processing equipment including tank vents and treating cylinders (Bolin and Smith, 2013). All of these actions can contribute to the lifecycle GHG emissions for timber rail ties.

Figure 7. Timber rail tie.

Based on the existing literature, most lifecycle GHG emissions assessments of timber rail ties do not consider the range of emissions, including CO_2 absorption from the atmosphere during photosynthesis. When GHG emission savings from biofuel usage, carbon storage, and avoided fossil fuel emissions are considered, these savings are greater than the carbon emissions that result from wood product manufacturing (Bergman et al., 2014). For example, when carbon storage of trees is considered, one study determined that concrete rail ties released 5.8 times more GHG emissions than timber rail ties (Bolin and Smith, 2013). Therefore, when sustainable forestry is practiced, the amount of carbon released each year through manufacturing timber rail ties does not exceed the carbon absorbed in that year and timber rail ties are considered “carbon neutral” (Bergman et al., 2014). When these negative carbon credits are considered in lifecycle analyses, timber rail ties have been found to emit less GHG emissions than concrete rail ties (Bergman et al., 2014). Any differences in the net carbon emissions from using different types of wood may be minimal (Bergman et al., 2014). However, because most lifecycle analyses do not consider sustainable forestry practices or stored carbon, most studies find that concrete rail ties have lower GHG emissions.

The largest amount of GHG emissions for timber rail ties results from the disposal phase, which accounts for 17 to 34 percent of their lifecycle GHG emissions. Three methods of timber disposal exist: recycling, adding to landfill, or incinerating with or without energy recovery. Recycling creosote-treated rail ties for energy recovery can offset fuel use by 20 times compared with the energy recovery from landfill disposal (Bolin and Smith, 2013). If all annually replaced timber rail ties in the United States (approximately 20 million rail ties) were recycled for energy (incinerated), it would offset the GHG emissions and fossil fuel use of about 100,000 U.S. residents (Bolin and Smith, 2013).

Depositing timber rail ties in landfills has the potential to produce methane (CH_4) at a rate of 0.09 kilograms of methane per kilogram (kg CH_4/kg) of wood (Milford and Allwood, 2010), which contributes up to 21 percent of the total lifecycle emissions of timber rail ties (Crawford, 2009). Sending timber rail ties to landfills can result in 100 to 180 times more GHG emissions compared with concrete recycling (Rempelos et al., 2020).

Biogenic CO_2 emissions from incinerated wood dominate overall lifecycle environmental costs for timber rail ties. Incineration without energy recovery can be considered carbon neutral if reforestation is considered, due to carbon sequestration during wood growth. As they grow, trees sequester and store carbon. Carbon sequestration ceases after the wood is harvested, and the decay process begins. Carbon that was stored in timber is emitted during burning or decay, balancing any consideration of stored carbon in the lifecycle assessment. Each timber rail tie contains about 71 pounds of carbon, which comes from the removal of 260 pounds of CO_2 while the tree grows (Smith and Bolin, 2010). Incineration of timber with energy recovery can generate three kilowatts per kilogram (kWh/kg) of wood (Milford and Allwood, 2010) and the associated energy savings would offset 53 to 75 percent of the energy consumed to make new timber products (Bergman et al., 2014). The GHG compounds that are released during incineration, as well as ash outputs, can be combusted in a boiler with scrubbers or electrostatic precipitators that can remove harmful chemical constituents (Diaz et al., 2022). Living trees can diminish the environmental impacts of timber incineration over time even further due to carbon sequestration. However, high-density hardwoods, the type of wood typically used for timber rail ties, take 50 to 70 years to reach maturity before harvest. Thus, it can take newly planted trees more than 100 years to recapture the atmospheric CO_2 emissions from incinerated hardwood (Diaz et al., 2022).

Increase in timber usage can contribute to deforestation as large amounts of trees are harvested and the availability of quality hardwood declines. In turn, this can lead to more timber being cut from less desirable species, particularly softwoods, that are less resistant to decay and need to be chemically treated (Manalo et al., 2009). Wood treated with chemicals has a prolonged service life, which can allow trees to be harvested less frequently, thus conserving forests. However, wood treated with chemicals for preservation raises concerns about their toxicity. A vast majority of timber rail ties in the United States are treated with creosote, but timber rail ties can also be treated with CCA, copper-boron-arzole, or pentachlorophenol. Timber rail ties used on bridges are typically treated with copper naphthenate. CO_2 and CH_4 are emitted during the treatment of wood, and chemical leaching and evaporation occurs during the service life of the rail tie. Some concerns regarding the use of CCA, pentachlorophenol, borate, and creosote as chemical treatments are described in Figure 8.

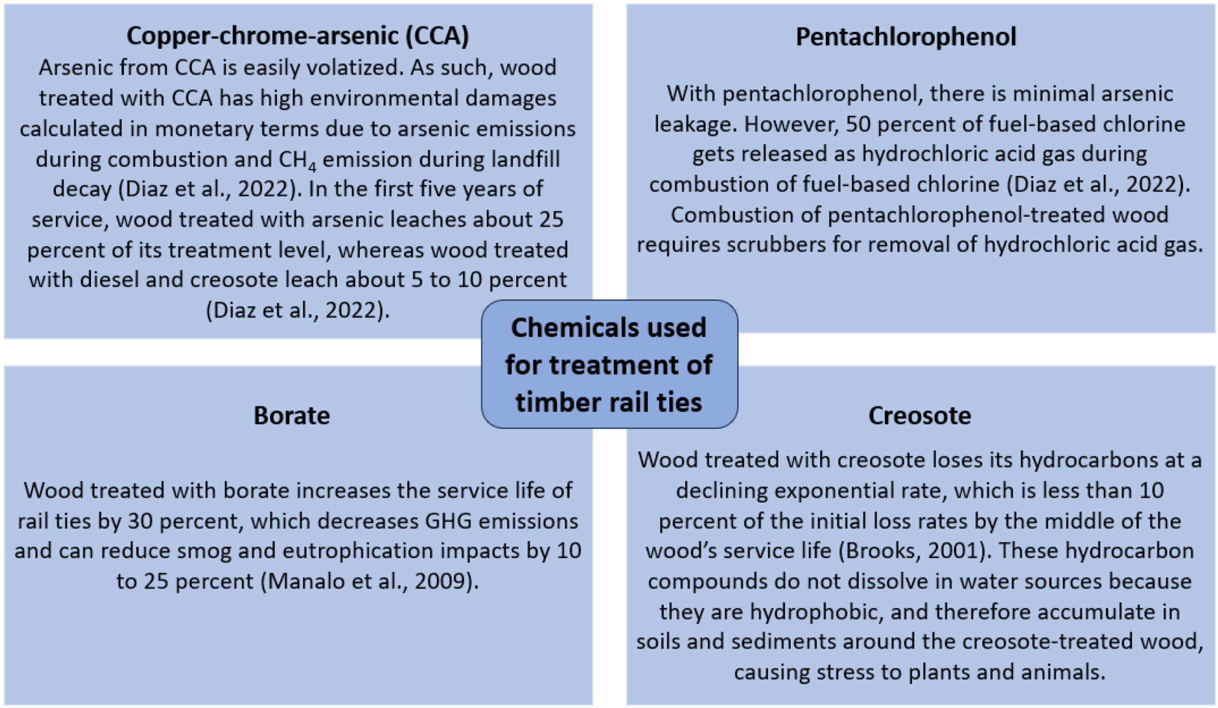

Figure 8. Chemicals used to increase the durability of timber rail ties.

3.2 Benefits

Hardwood timber rail ties are adaptable, as they can be used with all types of railway track and are easy to work with and replace (Manalo et al., 2009). Unlike concrete rail ties, timber rail ties do not require any specialized assembly equipment, which is desirable for line projects where track time and/or labor resources are limited (Manalo et al., 2009). Timber rail ties are flexible and are more resistant to vibrations from dynamic loads in railway track systems compared with concrete rail ties (Kaewunruen et al., 2018).

Despite being relatively lightweight (Manalo et al., 2009), timber rail ties are durable, especially when chemically treated with water-borne, inorganic salts (including copper, chrome, arsenic, and boron) and oil-borne organic compounds (e.g., creosote and pentachlorophenol) (Diaz et al., 2022). Treating a timber rail tie with creosote or other oil-borne preservatives protects the rail tie from insects and decay from fungi as well as protecting the interior of the rail tie from decay while in-track when rainwater enters cracks (Amburgey et al., 2003). Treatment for wood preservation can extend the service life of a timber rail tie by 20 to 40 times that of untreated wood for very little added financial cost (Bolin and Smith, 2013). Creosote-treated ties have a service life of 19 to 30 years, which could extend to 50 years depending on the climate (Smith, 2007). Creosote-treated rail ties are relatively inexpensive, costing upwards of $43 U.S. dollars[4] each, compared with steel and composite rail ties, which cost over $99 U.S. dollars[5] each (Smith, 2007).

[4] In 2024 U.S. dollars. The initial value reported was approximately $28 in 2007 U.S. dollars and was adjusted for inflation.
[5] In 2024 U.S. dollars. The initial value reported was approximately $65 in 2007 U.S. dollars and was adjusted for inflation.

3.3 Drawbacks

Untreated timber is vulnerable to degradation from timber rotting, splitting, insects, and fungal decay—the latter being the most frequent form of failure (Manalo et al., 2009; Bolin and Smith, 2013; Ferdous et al., 2015). Figure 9 provides an example of weathered timber rail ties. Softwood is more resistant to fungal decay than hardwood, yet is more susceptible to end-splitting, gauge-spreading, and spike hole enlargement (Kaewunruen et al., 2018). As such, timber rail ties require high maintenance; in the United States, the railway industry replaces 3.7 percent of the 620 million timber ties currently in use annually (Smith, 2009).

Figure 9. An example of timber rail ties under muddy conditions and experiencing weathering.

Although treating wood increases the durability and longevity of the timber rail ties, some treated wood products are carcinogenic (Diaz et al., 2022). Creosote-treated timber can have creosote levels that far exceed the critical limit set by the European Union, demonstrating its toxicity, as this preservative should be treated as hazardous waste during disposal (Manalo et al., 2009). Consequently, concerns over worker safety and environmental problems have led to a reluctance to recycling timber. Because scrubbers are not 100 percent effective, the incineration of treated timber rail ties is generally unaccepted by workers and the public due to the toxicity of the ash, in addition to the high cost of this procedure (Manalo et al., 2009). Moreover, the U.S. Environmental Protection Agency has updated its regulations related to the combustion of municipal solid waste, proposing more stringent emission limits in emission guidelines (*Standards of Performance for New Stationary Sources and Emission Guidelines for Existing Sources: Large Municipal Waste Combustors Voluntary Remand Response and 5-Year Review, 2024*). These standards would further impact the waste-to-energy process used in timber rail tie disposal.

In summary, treating timber rail ties with chemicals such as creosote can extend the service life of timber rail ties, requiring less maintenance and fewer early replacements than non-treated timber rail ties. However, the chemicals used to treat timber rail ties can be toxic and timber rail ties cannot be sustainably disposed of at the end of their service life, which adds to their lifecycle GHG emissions.

3.4 Disposal

Unlike other rail tie materials, timber is not suitable for re-use in track systems once these rail ties complete their service life or experience failure and breakage. During the disposal process, timber rail ties accrue GHG emissions as they are transported away from their installation site and to the disposal site. Other environmental impacts include biogenic emissions as timber breaks down as well as chemical leaching from timber rail ties that are treated with preservatives like creosote. Chemicals from treated timber rail ties can infiltrate the soil and groundwater as their compounds break down when discarded in a landfill.

However, research suggests that creosote can be recovered through a pyrolysis process that produces biochar ashes. Biochar can then be re-purposed as filtration, used to improve soil quality by reducing acidity and nutrient leaching, and can sequester carbon. Specifically, creosote-treated timber ties that were pyrolyzed to 700 degrees Celsius resulted in residual creosote of 0.06 percent by weight of the original tie (Gonzalez et al., 2020). Because no trace metals were found, the treated rail ties met the qualification of a soil amendment under the European Biochar Certificate (Gonzalez et al., 2020), an industry standard developed to ensure sustainable biochar production with minimal agronomic impacts.

In FRA's 2023 Request for Information on potential uses and options for the disposal or repurposing of used creosote-treated railroad ties (*Request for Information Regarding Uses for Used Creosote-Treated Railroad Ties*, 2023), several companies and organizations responded to describe their proposed solutions for the disposal of creosote-treated timber rail ties. These solutions included converting used rail ties into biochar; continuing existing waste-to-energy processes for rail tie disposal, such as conversion into renewable natural gas; captured carbon through pyrolysis; transforming rail ties into biofuel for use in diesel, kerosene, naphtha, and other transportation fuels; using rail ties as a biofuel stock in cement kilns to reduce GHG emissions from cement manufacturing; and converting rail ties to hydrogen for fuel use.

4. Other Materials

In addition to concrete and timber, rail ties can also be made of steel and plastic composite. However, steel and composite represent a significantly smaller portion of rail ties in the United States (0.6 percent) (Smith, 2019). Although these two materials are not commonly used in the United States, they are discussed in this report to provide a holistic view of the materials used in the rail tie industry.

4.1 Steel

Steel rail ties were introduced in the late 1800s due to the declining abundance of timber (Ferdous et al., 2015). Steel can weigh less than timber, be easier to handle, and have a longer service life. Additionally, steel can have a lower initial cost than timber, use less material, and require less maintenance. Another benefit of steel rail ties is that they are largely recyclable and can be re-used or repaired to extend their service life.

Figure 10. Steel rail tie. Image credit: Adobe Stock.

However, there are drawbacks to this material. Steel is only suitable for rail travel with speeds less than 100 miles per hour (mph) (Manalo et al., 2009). This is because the properties of steel that make this material relatively lightweight also make it less resilient against impacts from frequent and heavy trains, such as those used for high-speed rail. Additionally, steel rail ties are more susceptible to corrosion, cracking (due to fatigue), and have high electrical conductivity (Manalo et al., 2009; Ferdous et al., 2015). Like concrete, steel cannot be used in signaled track without rail pads and insulators, both of which contribute further to lifecycle GHG emissions.

The greatest source of lifecycle GHG emissions for steel rail ties is the manufacturing process (Milford and Allwood, 2010). First, the iron and carbon materials need to be heated to very high temperatures to produce steel, which then needs to be cast, cut, and shaped. Additional lifecycle emissions accrue as the steel rail ties are transported to the installation site, installed, and undergo maintenance throughout their service life. At the end of their service life (approximately 50 years), steel rail ties can be recycled and used again. Approximately 85 percent of steel used for steel rails is recycled by the steel industry (Kiani et al., 2008), indicating that there is opportunity for steel rail ties to be recycled as well.

4.2 Composite

Composite rail ties are infrequently used in U.S. rail systems and continue to be evaluated and tested in laboratory settings to further understand how these rail ties perform. Composite rail ties are typically made of post-consumer recycled plastic and asphalt, and their reinforcement varies dramatically by manufacturer. Composite rail ties have been tested in laboratory and field settings with speeds around 40 mph. Results from composite rail tie testing indicate that track curvature and train speeds do not significantly alter composite rail tie performance (Gao and McHenry, 2021), making this material a potential option for use in freight and passenger rail.

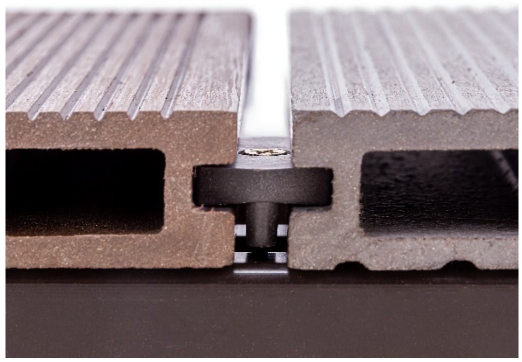

Figure 11. Plastic composite, the material used in composite rail ties. Image credit: Adobe Stock.

Composite rail ties are designed to mimic the attractive properties of timber rail ties and can serve as a potential alternative. Composite rail ties are less susceptible to decay and can provide a longer service life, but generally have a higher up-front cost compared with timber rail ties (Ferdous et al., 2015). Moreover, composite rail ties have limited strength and stiffness, in addition to experiencing failures that are not observed in timber rail ties. Composite rail ties can experience several issues throughout their service life, including center cracking and bending, cracked tie plates, spike-hole cracks, and gauge-widening. The two primary causes of failure are spike-hole cracking and center cracking, which are caused by fatigue (Gao and McHenry, 2021). Another significant drawback of this material is thermal expansion. (Refer to Section 5.2 Temperature Change, for additional information on rail tie performance and temperature change.)

Although composite rail ties undergo the same recommended testing as concrete and timber rail ties, testing criteria and design guidelines specific to composite rail ties are needed. Gao and McHenry (2021) found that spike-hole cracks, one of the primary causes for composite tie failure, developed after tonnage increased, and not during installation or removal. This finding demonstrates that the existing industry standards for determining optimal pre-drill hole size for this material are inadequate and need to be determined specifically for composite material.

Given the drawbacks discussed here, and the infrequent use of composite rail ties, there is a need for additional research and studies to evaluate the lifecycle emissions and greater environmental impact of this material.

5. Resilience and Climate Change

Transportation infrastructure is vulnerable to deterioration and damage from adverse weather conditions, which exacerbates ordinary wear and tear. Understanding the vulnerability and sensitivity of transportation infrastructure to extreme weather events attributed to climate change is important in considering the greater environmental impacts of different rail tie materials.

More frequent and extreme weather conditions due to climate change can impact the operational life of different rail tie materials. This section covers the impacts of flooding, sea level rise, temperature change, and fire on rail ties. There is an opportunity for additional research on how different aspects of extreme weather events affect rail tie performance and the types of rail ties that are best suited in different environments.

5.1 Flooding and Sea Level Rise

More frequent and intense weather events due to climate change can cause flooding, inundation, and increased moisture in areas that were previously not subjected to these conditions (Schreider et al., 2020). Climate change is also a major driver of sea level rise, which increases the frequency of coastal flooding (Taherkhani et al., 2020).

These conditions can cause ground-based disturbance and instability, which can alter the track system and impact the integrity of rail ties. For example, steel rail ties have a higher level of wheel-rail interaction because of their track design, which can lead to significant ground vibration. This vibration creates a buoyancy behavior that leaves the ballast underneath rail ties more vulnerable to displacement during a flood event. Concrete, timber, and composite rail ties can better stabilize track as they do not exhibit this buoyancy behavior. As such, they can reduce flow velocity during increased rainfall events, floods, or water runoff (Kaewunruen et al., 2018). Additionally, stress can wear down top soil and form mud, which can come into contact with ballast underneath rail ties during floods or periods of increased rainfall (Kaewunruen et al., 2018). Increased amounts of mud can impede a track's ability to drain out moisture and results in track failure; impacts from mud can occur with any type of rail tie material.

Figure 12. Concrete rail ties submerged during a flash flood. Image credit: Adobe Stock.

Moisture from rain, frost, snow, dew, and flooding can negatively impact the properties and operational life of all rail ties (Ferdous et al., 2015). Specifically, excessive moisture can damage the load distribution pattern at the rail tie–ballast interface, which can cause increased wear and tear not only on the rail tie but also on the larger track infrastructure.

Furthermore, timber rail ties often decay from high moisture content, which leads to a loss in vertical stiffness. This can result in excessive track settlement and deformation (Kaewunruen et al., 2018). At higher moisture levels, steel rail ties can oxidize and corrode. Similarly, if not drained properly, composite rail ties can absorb water and lead to reduced performance. Composite rail ties can also be damaged if water leaks between fasteners and composite materials.

Coastal area conditions, such as interactions with saltwater due to rising sea levels and increased flooding, can also impact rail tie materials. Specifically, steel is easily corroded by saltwater (Ferdous et al., 2015), while concrete deteriorates by chloride penetration and carbonation (Diaz et al., 2022). Composite rail ties are also susceptible to water degradation (Ferdous et al., 2015) and therefore are also not recommended for use in coastal areas that are susceptible to flooding or periodic inundation.

Concrete rail ties may be relatively less susceptible to water inundation than other rail tie materials. However, water that has accumulated inside cracks in concrete rail ties can be expelled or trapped when the track system closes after train passage. Further, water entering and flowing through pre-existing cracks in the concrete rail tie may cause further deterioration, impact structural capacity, and reduce service life; periodic inundation from rain or flooding can reduce the cyclic life of cracked, pre-tensioned concrete rail ties (FRA, 2019).

5.2 Temperature Change

Rail ties can experience structural changes due to fluctuating temperatures. Generally, composite and steel rail ties are more susceptible to fluctuating temperatures, while concrete rail ties can better retain their structural integrity during temperature fluctuations. However, increased average temperatures and more frequent extreme high temperatures can lead to rail deformation and rail track buckling (misalignments in continuous welded rail track) regardless of rail tie type (Nemry and Demirel, 2012).

Composite rail ties are more sensitive to changes in temperature than timber rail ties and can therefore be prone to widening and bending (Ferdous et al., 2015; Gao and McHenry, 2021): the top of the composite rail tie will experience a higher ambient temperature than the bottom, and this difference in temperature causes the rail tie to bend and widen. Therefore, composite rail ties are best suited for use in areas that have a consistent climate throughout the day and year. They are less suitable for use in areas that experience a shift in temperature throughout the day, such as the high desert regions of the southwestern United States. Additionally, composite rail ties are easily degraded by ultraviolet (UV) light (Ferdous et al., 2015), making them inadequate for use in regions that receive high UV radiation (e.g., near the equator), such as southern New Mexico and Arizona. Despite these climate considerations, composite rail ties have been installed globally, including in the United States, most often as a replacement for timber rail ties (Ferdous et al., 2015). In areas with high UV radiation, concrete rail ties may be more suitable than composite rail ties, as they are less susceptible to impacts from UV radiation.

Figure 13. An example of rail buckling due to high temperatures on a track with timber rail ties.

Rail ties provide resistance to any lateral movement of rails, but during high temperature events, this usual side-to-side movement may overcome the lateral resistance of rail ties, leading to rail buckling (Figure 13). Timber and steel rail ties exhibit poor resistance to lateral movement in such scenarios, whereas concrete rail ties can better retain their original alignment and geometry (Kaewunruen et al., 2018). However, timber rail ties treated with creosote can withstand temperature changes, vibration, and compression and are more resistant to moving out of position (Smith, 2007).

Additionally, rail ties can also be vulnerable to contraction during cold onsets. Periods of extreme low temperature can lead to unexpected failures of steel and composite rail ties. Steel, and the resin in composite rail ties, can become very brittle, and ice-stiffened tracks can damage rail ties, leading to excessive ground-borne noise and vibration (Kaewunruen et al., 2018). Ice-stiffening can also cause ballast dilation, sub-ballast cracking, and frozen rail joints throughout the track infrastructure. Freeze–thaw events can lead to concrete rail tie damage by causing internal pressure and damage during water expansion (Kaewunruen et al., 2018; Riding et al., 2024).

5.3 Fire Resistance

With the growing frequency and intensity of wildfires (Westerling and Bryant, 2008; Abatzoglou and Williams, 2016), there is a need to understand how rail ties and larger track infrastructure are impacted. Although studies have evaluated the fire resistance of different rail tie materials (Ferdous et al., 2015), most of this research has focused on resistance to fire from welding and track operation, not wildfires. A deeper understanding of how rail materials fare in increasingly warm and dry climates may lead to innovative strategies to reduce deterioration, increase resiliency, and reduce railway fire risks.

6. Areas for Future Research

6.1 Cement Mix Design Optimization

As discussed, rail ties have the potential to be large GHG emitters throughout their lifecycle. This has led several organizations to evaluate innovative ways to reduce GHG emissions in rail tie applications. Organizations, including private companies and universities, are beginning to evaluate mix design of cement to adjust the composition and replace certain components with more environmentally friendly options. These mix designs may result in a lower global warming potential and, as an added benefit, reduced installation costs due to sourcing of local materials and less water usage. However, additional research into lower CO_2 concrete mixtures is needed to ensure that optimized mix designs meet the specific needs of the rail community.

6.2 Emerging Timber Rail Tie Treatments

New methods of treating timber rail ties are being explored. One such treatment is the carbon compound 4,5-Dichloro-2-n-Octyl-4-Isothiazolin-3-One (DCOI), which is an oil-borne wood preservative used in drywall, pool liners, shower curtains, boats, and wood utility poles. Laboratory testing of DCOI has shown that this treatment is effective in preventing fungal decay and termites, which indicates that DCOI may also be suitable to treat timber rail ties (Viance, 2024). Unlike other timber treatment compounds, DCOI does not contain heavy metals such as zinc, arsenic, or copper. DCOI may also result in fewer lifecycle emissions due to a lower amount of energy and water needed for its production and a wider range of disposal options (Viance, 2024). Use of DCOI in timber rail ties is still in the research and development stage and has not yet been used as a wide-scale treatment option.

Another timber rail tie treatment option in the testing stage is the use of asphalt. Asphalt is being explored due to its ability to “weatherproof” and seal cracks in timber rail ties. An asphalt coating could mitigate the impacts that timber rail ties experience from UV exposure, water, decay, and insects (Asphalt Materials Inc., 2024). However, coating timber rail ties in asphalt makes a visual assessment of a rail tie’s condition challenging, and the production and disposal of asphalt treated rail ties may accrue additional lifecycle GHG emissions.

6.3 Other Research Gaps

There are numerous studies that evaluate the lifecycle GHG emissions of different types of rail ties (Kiani et al., 2008; Crawford, 2009; Bolin and Smith, 2013; Lim et al., 2023). Although each study reports net GHG emissions and global warming potential, it is challenging to compare results across different studies due to the different assumptions made in each study for parameters such as service life, the number of tie replacements needed during operation, and associated maintenance, among other assumptions in the manufacturing and decommissioning stages. There is no consensus in the literature for a quantitative range of emissions for different rail tie materials. Ultimately, more research is needed.

There is also an opportunity for additional research on materials other than concrete and timber. Although timber is the most used rail tie material, followed by concrete, there is an opportunity to research other innovative and emerging materials. This research could be supplemented by further consideration for existing materials like steel and composite, specifically, more robust design and installation guidelines that are unique to steel and composite rail ties. Such testing and recommendations are beginning to emerge (Gao and McHenry, 2021) and could be expanded upon.

Moreover, there are currently no environmental product declarations (EPD) for rail ties in the United States. An EPD identifies the lifecycle environmental impact of a product and can be used to inform product design and procurement decisions. Although Product Category Rules (which influence EPDs) for rail ties have been developed, EPDs themselves have not been developed for rail ties. Therefore, there is a need to develop rail tie–specific EPDs to promote sustainable practices in the rail tie industry.

As discussed in Section 5, Resilience and Climate Change, there are currently few studies that assess the sensitivity of rail ties to more frequent and intense weather events attributed to climate change. Thus, more research is necessary to evaluate the resiliency of rail ties during climate-related events.

7. Conclusion

This paper synthesizes the results of various rail tie reports and studies that evaluate the lifecycle GHG emissions of concrete, timber, steel, and composite rail ties. Of the four rail tie materials, concrete has the lowest lifecycle GHG emissions due to fewer rail ties needed per track mile, fewer maintenance requirements, and a longer service life compared with other rail tie materials. Further, due to their high durability and heavy weight, concrete rail ties are suitable for both freight and high-speed rail.

Timber is an attractive option for rail ties due to its low upfront financial cost and the resupply of trees for wood production from planting as well as the reduced lifecycle GHG emissions due to carbon storage in trees. However, the harvesting of trees to manufacture timber rail ties and the chemical treatment of timber rail ties to prevent decay both contribute to this material's relatively high GHG emissions compared with other materials. The toxicity from chemicals used to treat timber rail ties results in additional environmental safety and public health concerns, while any stored carbon in the wood is released back into the atmosphere during the disposal stage. Moreover, it can take newly planted trees over 100 years to recapture the atmospheric CO_2 emissions from incinerated wood. Studies that have considered stored carbon have indicated timber rail ties could result in fewer lifecycle GHG emissions than concrete rail ties, but more research is needed.

Steel and composite were initially seen as viable alternatives to both timber and concrete rail ties, but these two materials currently have physical and chemical properties that limit their widespread use. Additional research and development are needed to optimize the potential of these materials before they can be substitutes for timber and concrete rail ties. Additionally, more information is needed to determine the lifecycle GHG emissions associated with steel and composite rail tie materials.

There are many other opportunities to continue research in the rail ties field to increase understanding of and improve the materials used for rail tie production. For example, the mix design of cement for concrete rail ties and the types of compounds used to chemically treat timber rail ties may be optimized to further reduce lifecycle GHG emissions. Additional research is also needed to determine best practices in calculating lifecycle GHG emissions for rail tie materials. Further research can help determine a uniform set of assumptions to estimate the lifecycle GHG emissions for each material because the existing literature does not have a consensus on the range of those emissions.

Finally, additional research is needed to determine the best types of rail tie materials to withstand the impacts of climate change, such as increased flooding, fluctuations in temperature, and wildfires.

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Abbreviations and Acronyms

ACRONYM	DEFINITION
CCA	copper-chrome-arsenic
CH_4	methane
CO_2	carbon dioxide
EPD	Environmental Product Declaration
DCOI	4,5-Dichloro-2-n-Octyl-4-Isothiazolin-3-One
FRA	Federal Railroad Administration
GHG	greenhouse gas
kg	Kilogram
km	Kilometer
kWh	Kilowatt hour
mph	miles per hour
U.S.	United States of America
UV	ultraviolet