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Life cycle assessment of football fields in Nordic climates: Comparing artificial and natural turf systems

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ABSTRACT

Sport is more than just a game—it's a global phenomenon that shapes cultures, economies, and communities. Football, the world's most popular sport, is a prime example. Yet beneath the surface lies an overlooked environmental cost. As the climate crisis accelerates, the sprawling network of football facilities—stadiums, training grounds, and infrastructure—emerges as a silent contributor to environmental degradation and the transgression of planetary boundaries. Two common types of fields exist: artificial and natural turf. Research on environmental impacts of these turfs remains limited, especially in cold climates. This study presents a life cycle assessment of 1 m^2 artificial and natural football turfs in Nordic climates, evaluating their environmental impacts such as global warming potential, eutrophication potential and ecotoxicity potential across construction, use, maintenance, and end-of-life phases over operational lifespans of 10, 20 and 30 years. Natural turf exhibited the highest overall environmental impacts over the operational lifespan, e.g. the global warming potential was 30.6 kg CO_2 eq/m^2 while the artificial turf reached 15.6 kg CO_2 eq/m^2. During the construction phase, artificial turf generated significant emissions, mainly from material production. In the use phase, natural turf showed the greatest impacts due to diesel consumption and fertilizer application. At the end-of-life stage, artificial turf's sand and infill were reused, while the turf carpet and shock pad were incinerated for energy recovery. However, without recycling, artificial turf would represent the highest environmental burden among the evaluated alternatives. Implementing effective recycling and energy recovery strategies is essential to mitigate its environmental impact. Furthermore, sourcing turf materials locally, combined with substituting conventional maintenance equipment with electric robotic alternatives, can further reduce overall environmental impacts.

1. Introduction

Climate change stands as one of the most pressing and formidable challenges of our time, threatening not only the future but also the very core of biodiversity and human well-being in the face of global climate crises (Steffen et al., 2015). With unsustainable land use, the Earth's ecological stability is increasingly threatened. The framework of planetary boundaries (PB) defines Earth's system which humans can operate safely, but crossing these boundaries could cause not only environmental catastrophe but also consequences for economic development and equity (Tomalka et al., 2024). There are in total nine PBs, where seven of these are included in land management: climate change, freshwater change, biosphere integrity change, novel entities, land-system change, biogeochemical flows and atmospheric aerosol loading (Rockström et al., 2009). Larger sports arenas, like football fields, also negatively affect these boundaries but are not well investigated when it comes to research.

Around 265 million people play organized football (Kunz, 2007), which corresponds to 4 % of the total world population. In Sweden, football is the top-rated sport (World Population Review, 2024), accounting for one-third of the nation's sports activities (Swedish Football Association, 2024). However, due to the Nordic countries' cold climate, with snow and freezing temperatures, it is hardly possible to play football the whole year on natural turf (NT), so an alternative for yearly play is artificial turf (AT). Since most football fields are located in urban environments, land management becomes a crucial factor to involve when constructing a new field. According to the Swedish Football Association (2024), there are over 5000 fields in Sweden where 69 % are

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NT fields, 16 % are AT fields and the rest are gravel and hybrid fields. A major difference between the fields is the concept of living versus "dead" land management. NT consists of living grass, whereas AT is composed of artificial plastic grass, resulting in "dead" areas where nothing on or beneath the surface is alive. In Sweden, approximately 5,700,000 m^2 of "dead" area exist, assuming each AT field covers 7140 m^2 of land (FIFA. 5, 2024a). Therefore, NT makes a more positive contribution to a biodiverse landscape compared with AT. Regardless of the type, a football field does not typically support high levels of biodiversity. Nevertheless, both AT and NT are essential in Sweden to accommodate the annual demand for football play.

Despite football being one of the most widely played sports globally, with extensive infrastructure dedicated to both AT and NT fields, there remains a notable lack of comprehensive research on their environmental impacts from a life cycle perspective. To date, there are few studies which have provided such analyses. One study assessed the life cycle impact of football turfs, focusing on a Mediterranean climate (Russo et al., 2022), which limits its applicability to Nordic conditions such as those in Sweden, especially in maintenance routines. Although existing life cycle studies have examined both AT and NT, they have primarily focused on microplastic dispersion and leaching during the life cycle phases (Nishi et al., 2022; Zeilerbauer et al., 2024). Moreover, there is a scarcity of studies of the broader understanding of environmental trade-offs between the two turf alternatives. This study is therefore one of the first to address this critical research gap by applying a life cycle perspective to turf systems in a Nordic climate, contributing novel insights to an underexplored yet environmentally significant area.

This study aims to conduct a comprehensive cradle-to-grave life cycle assessment (LCA) of artificial and natural football turfs, encompassing the construction, use, maintenance and end-of-life phases over operational lifespans of 10, 20 and 30 years. The study will examine the energy demand, climate impact and several other relevant environmental impacts of these football fields, in a Swedish context.

2. Literature overview

The first generation of AT was introduced in the 1960s and consisted solely of a carpet-like surface without any infill materials (Cheng et al., 2014). In the 1980s, a second-generation of AT entered the market, featuring significant advancements in fibre technology and performance. This version incorporated sand infill to enhance stability and playing characteristics (Russo et al., 2022). The third generation (3G), which represents the latest approved technology and entered the market in the late 1990s, utilizes a carpet structure composed of synthetic fibres designed to closely replicate the appearance and performance of natural grass. It also includes a performance infill with sand underneath to obtain the properties of natural turf (Cheng et al., 2014), see Fig. 1. From a maintenance perspective of environmental impacts, AT fields have several benefits, since they do not require water, fertilizers nor herbicides, as the traditional NT fields do (Barnes et al., 2022; Russo et al., 2022).

The third generation contains a shock pad often made by polyethylene (PE), a carpet or backing made from latex or PE, sand and performance infill, which is commonly recycled shredded tyres called styrene butadiene rubber (SBR), and the grass or fibres made from PE and polypropylene (PP), which are attached to the backing (Cheng et al., 2014). During the maintenance phase, weekly brushing and harrowing are crucial for levelling and preventing compaction of the performance infill. Other maintenance processes include annual deep cleaning of the turf and performance infill to remove organic matter, as well as snow removal, when needed. Lastly, the disposal phase of AT involves options such as landfill, energy recovery or material recycling (Callenmark, 2024). However, AT fields pose a significant concern due to their microplastic content, which can have adverse effects on human health. These microplastics can leach heavy metals and contain volatile organic compounds (VOCs), raising serious environmental and public health concerns (Barnes et al., 2023; Huang et al., 2023; Nishi et al., 2022; Rittelmann-Woods et al., 2023).

NT is composed of grass seeds that are sown in the soil, creating a living turf suitable for play. In total there are three layers from the top of the grass to the bottom: grass cover, upper rootzone and lower rootzone (FIFA. 2, 2024b), see Fig. 1. The NT also needs to be maintained regularly, and on a weekly basis, with mowing and irrigation and yearly maintenance of aeration, dressing and fertilizing (Callenmark, 2024). In urban ecosystems, NT fields contribute significantly to green infrastructure by preventing soil erosion, sequestering carbon, and supporting stormwater management through filtration and runoff mitigation. Despite this, NT fields are often met with criticism from various stakeholders – such as homeowners, land managers, and policymakers – due to the intensive resource demands, including water, fertilizer and labour (Elnaggar, 2024). It is important to note that while ornamental lawns can contribute to carbon sequestration, sports fields, such as football and athletic fields, may not contribute to long-term in situ carbon storage. This is primarily due to the intensive maintenance practices and frequent surface restorations required, which disrupt the soil and vegetation, thereby limiting their capacity to store carbon (Townsend-Small et al., 2010).

One important factor when comparing AT with NT is the operational life span in the study. Zeilerbauer et al. (2024) examined the microplastic from an AT and environmental impacts perspective over a 30-year period in Norway, providing a full cradle-to-grave analysis of all process steps, from raw material extraction and construction to renovation, maintenance and end-of-life. However, an interesting aspect that remains unclear is the exact scope of the 30-year period and what it encompasses. The Research Institute of Sweden (RISE) claims that one AT has a lifetime of approximately 10 years (RISE and Konstgräsguiden, 2021), which the International Federation of Association Football (FIFA) also confirms (FIFA. 2, 2024b). Hence, Zeilerbauer et al. (2024) include "pitch deconstruction", which may imply that the author is referring to three AT replacements being included within the 30-year operational lifespan.

What also can be concluded is that budgets and research about maintenance and management of football fields remain very rare in Europe (Curk et al., 2017), even though football fields are considered to be the toughest of all turf areas to manage (ÇelİK et al., 2019). It is also important to note that NT fields require substantial inputs of water and fertilizers (Barnes et al., 2022; Kopecký et al., 2014), where water is increasingly scarce (Emergency information from Swedish authorities).

The global proliferation of AT fields is unprecedented. FIFA establishes the quality standards for these fields, but there is a dearth of

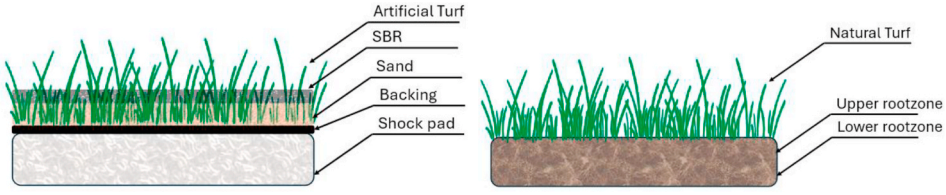

Fig. 1. To the left are the layers of an AT which include a shock pad, backing, sand, SBR and AT. To the right are the layers of a NT which include a lower rootzone, upper rootzone and turf.

information for field owners regarding their environmental impact (FIFA and FIFA Quality Programme For Football Turf, 2024). As new fields are being constructed, old fields require proper maintenance and disposal at their end-of-life stage. Hence, there is a demand for effective and improved disposal methods (Eunomia Research and Consulting Ltd, 2017). The main disposal alternatives are landfilling or incineration after separation from the infill (sand and SBR), but both alternatives are a non-favourable method, since they contribute to landfilling or add hazardous gases to the environment. An alternative approach to managing waste from AT involves recycling by shredding the material to manufacture new AT. However, this method faces significant challenges due to the poor mechanical properties of the plastics involved, which adversely affect the quality and durability of the newly manufactured AT (Liu et al., 2017), and for which there is a lack of recycling facilities in Europe (Callenmark, 2024).

The environmental impacts during the operational lifespan of these two types of turfs have not been thoroughly researched in the past. Life cycle assessment (LCA), as a standardized and comprehensive tool, plays a central role in assessing the environmental and human impacts of processes and materials, enabling decision-makers to identify more sustainable solutions (Xayachak et al., 2024). There are LCA studies when it comes to the microplastic of AT fields, but few in-depth analysis assessments between AT and NT when it comes to environmental impacts in Europe. One with focus of Switzerland (Itten et al., 2021), another based on that study with some focus on Norway (Zeilerbauer et al., 2024), and the last one with focus on the Mediterranean climate (Russo et al., 2022) – in other words only one focusing on the Nordic climate. This paper contributes to closing this knowledge gap, i.e. the paper is thus unique as it is one of the first paper assessing environmental impacts of both NT and AT for the Nordic climate. These current studies also consider a ten-year lifetime (Russo et al., 2022) or a 30-year period for both turfs with no specific replacement interval (Zeilerbauer et al., 2024). This paper covers a 30-year operational lifespan for both turfs, with replacement of the AT each 10th year and an infinity lifetime for the NT with recommended maintenance. So far, only Itten (Itten et al., 2021) and Zeilerbauer et al. (2024) has considered a 30-year operational lifespan for NT and AT. Given the limited number of studies on this topic, there is a scarcity of literature regarding the life cycle data of a football field, encompassing its construction, use, maintenance and end-of-life stages. There are also practical needs from stakeholders which are not well understood or balanced when it comes to environmental impacts and which this study will cover.

3. Materials and methods

The primary method for this paper was an LCA, following and inspired by the four phases based in ISO 14044 (Standardization et al., 2020) and the cradle-to-grave scope including raw material, construction, use phase, and end of life. This also corresponds to a full operational lifespan in other close related methods such as Product Environmental Footprint (PEF). The attributional system model "allocation, cut-off by classification – Unit" was applied (Wernet et al., 2016). Data were collected from published literature using a snowball sampling approach, rather than through a formal systematic review, databases (Ecoinvent 3.8) and personal communication with stakeholders (emails, group meetings, interviews). Experts and stakeholders in NT and AT within Swedish football provided input to validate key choices and assumptions. Additionally, a field test was conducted to measure fuel consumption during the maintenance of an AT turf. LCA models were developed using SimaPro software 9.6.0.1, with complementary calculations in MS Excel (for details, refer to Appendices, Supplementary materials, Tables 1–4). The LCA framework comprised goal and scope definition, inventory analysis, impact assessment, and interpretation. Iterative processes were employed to ensure the validation and accuracy of the goals, data and results (Standardization et al., 2020).

3.1. LCA – goal and scope definition

As mentioned, this study investigated the environmental impacts of football fields, from a life cycle perspective, and considering Swedish climate conditions. NT and AT were chosen as surface types due to the limited research on their environmental impacts from a life cycle perspective. The functional unit was defined as 1 m^2 of turf to accommodate varying field sizes beyond FIFA's standard 105 × 68 m. This allows the model's applicability to other uses, such as golf or alternative AT or NT fields. For AT, fields using SBR infill were selected, as it is the most common performance infill in the world (Russo et al., 2022) and in Sweden (Callenmark, 2024) and does not freeze in cold climates (Fältström et al., 2024). For NT, seed-based construction was chosen per FIFA recommendations (FIFA, 2023). Groundwork such as drainage and carrier layers was excluded, assuming equal requirements for both field types. Construction begins at the topsoil/lower rootzone for NT and the shock pad for AT (see Fig. 1).

Sundsvall, Sweden, was selected as the study site due to its central location. Primary inventory data were collected from adjacent AT and NT fields, using procurement records and stakeholder interviews. Data included materials, transport, maintenance, tools, and end-of-life processes. Diesel was assumed as the fuel for all maintenance machinery, based on expert input. Following Swedish Football Association guidelines, no AT refill was needed during one lifetime, and sand and SBR infill were assumed to be reused from expired AT (Falsafi et al., 2025). Secondary data from other Swedish stakeholders filled inventory gaps and validated assumptions. Table 1 presents the complete inventory overview. The case and lifetime were based on facility recommendations from facility managers at the Swedish Football Association (Callenmark, 2024).

3.2. Impact assessment

The LCA was conducted with a focus on six key environmental impact categories related to land management inspired by the PBs framework. These impact categories were selected based on their relevance to current environmental challenges and through consultation with stakeholders, including the Swedish Football Association. Firstly, primary energy demand (PED) was included due to the increasing energy demands of modern society, highlighting the need to understand which turf type and life cycle phase is most energy intensive. Secondly, the impact category climate change was assessed using the category indicator global warming potential (GWP), as emphasized by the Paris Agreement (European Union, 2016). Eutrophication potential (EP) and acidification potential (AP) were selected because fertilizers used in NT can lead to nutrient pollution (Sharma et al., 2013) and soil acidification (Guo et al., 2010).

Lastly, freshwater ecotoxicity potential (FEP) and terrestrial ecotoxicity potential (TEP) were included to assess the effects of microplastics present in ATs, but also other toxicity from fertilizers and diesel use. The inclusion of these metrics was driven by ongoing discussions among experts and stakeholders regarding the potential impacts of microplastics on human health and ecosystems. It should be noted that this study did not included the hazardous chemical leaching from microplastics, due to the extensive existing research in this area, e.g. de Haan et al. (de Haan et al., 2023), Nishi et al. (2022), Zeilerbauer et al. (2024). Carbon sequestration was not addressed in this paper, as the primary focus is on football fields, which are unlikely to contribute to long-term in situ carbon storage due to their intensive maintenance and surface management practices (Townsend-Small et al., 2010). The methods used for the impact assessment were Cumulative Energy Demand version 1.12 for the PED (focusing on non-renewable primary energy use), the Environmental Product Declarations (EPD) 2018 version 1.05 was used for GWP, EP and AP, and lastly, FEP and TEP were based on the ReCiPe 2016 version 1.09 Midpoint Hierarchist perspective.

Due to limited data on maintenance activities for AT, particularly brushing and harrowing, a field test was conducted at Bilbörsen Arena in Linköping, Sweden. Using appropriate equipment, including a tractor, the test began with refuelling at a designated platform. Brushing was performed for 40 min, after which fuel consumption was measured by refilling the tank with a litre gauge. Harrowing, requiring greater power due to increased resistance, was estimated to consume 1.2 times more fuel than brushing.

In the end-of-life phase, energy recovery via incineration was assumed for AT including the shock pad, reflecting common disposal practices for heavily used fields in Sweden. This was supported by stakeholder insights gathered during data collection. In contrast, SBR infill and sand were assumed to be reused in future AT installations.

Maintaining NT field data proved challenging, requiring validation through communication with turf producers, soil experts, and facility managers. Additional data were gathered from literature and supplier datasheets for both field types, compiled into a life cycle inventory (LCI) in Excel and normalized per m^2. Due to seasonal limitations in Sweden, both AT and NT were assumed to operate 24 weeks annually (April–October), with equal playing hours. Snow removal was excluded. AT fields were modelled with a 10-year lifetime which include all the layers (artificial turf, sand, infill and shock pad) covering three full lifetimes over 30 years. NT fields were assumed to have indefinite lifetimes with proper maintenance; therefore, no end-of-life treatment was considered at year 10 or 20, as regular maintenance continues without replacement. System boundaries are shown in Fig. 2; materials and processes are detailed in Table 1.

3.3. Inventory

Table 2 presents the results of the compiled inventory data, with calculation details and references available in the Appendices (Supplementary Materials, Table 3). For AT, manufacturing was assumed to occur in Lano (Belgium), including the turf carpet and shock pad. Sand and SBR infill were sourced from Brogård (Sweden) and Herning (Denmark), respectively. For NT, soil was transported from Timrå, and fertilizers and seeds from Gothenburg. Both fields incorporated material distribution systems. However, only the NT field included an irrigation system as part of its construction. During use, only NT received transported materials. At end-of-life, 85 % of AT materials were reused (infill and sand), while 15 % (carpet and shock pad) underwent energy recovery 7.9 km away.

Table 1
– Explanation of phases and processes in the inventory list of artificial and natural turf.

	Artificial Turf (AT)	Natural Turf (NT)
Construction	– Manufacturing of one AT of the third generation consisting of an artificial turf (fibres and backing), a shock pad, sand and performance infill (SBR). – Transport of materials from the manufacturer to the customer. – Machinery for installation.	– Manufacturing of one NT consisting of soil (sand and peat), seeds, fertilizers (NPK) and water. – Transport of the materials from the manufacturer to the customer. – Machinery for installation.
Maintenance	– Weekly: Brushing 3 times a week, harrowing 1 time every second week. – Yearly: Deep cleaning 1 time a year.	– Weekly: Mowing 2–3 times a week and irrigation 3 times a week. – Yearly: Aeration 5 times a year, fertilizing 3 times a year (spring fertilizers, season fertilizers and autumn/winter fertilizers), sand dressing one time a year.
End of life	– Transport to nearest incineration plant. – Machinery for deconstruction. – 85 % of the AT field goes to material recycling (performance infill and sand) while the rest, 15 %, goes to energy recovery (fibres, backing and shock pad).	– No end of life (continuous maintenance).

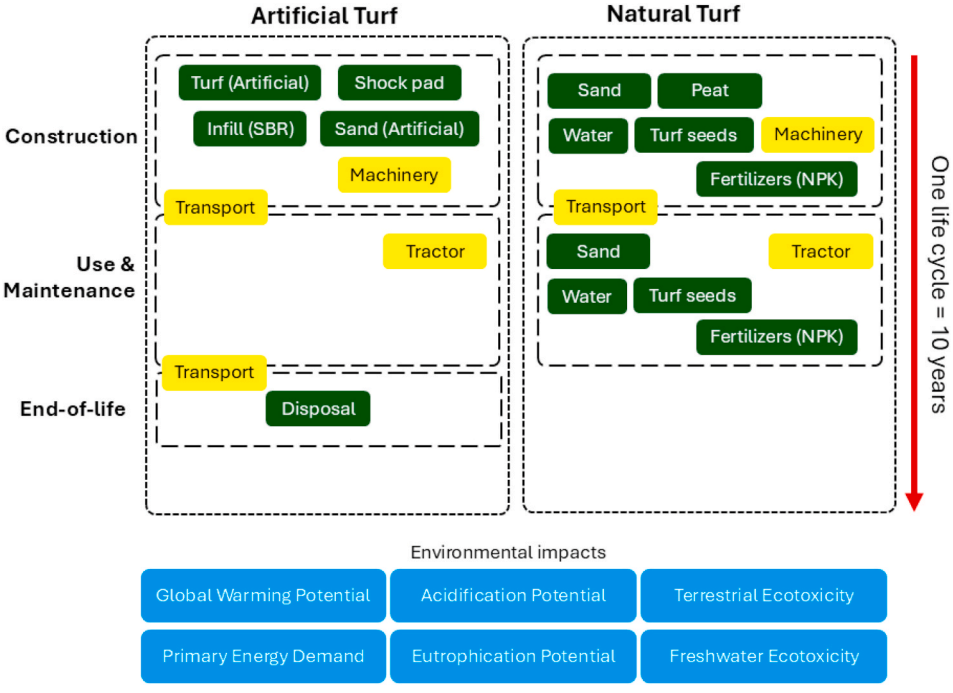

Fig. 2. System boundaries of AT and NT from the studied case. Dashed boxes represent each phase of the life cycle. Green boxes represent materials/assemblies, while yellow boxes represent processes. Light blue boxes at the bottom represent the chosen environmental impacts.

Table 2
The life cycle inventory (LCI) for 1 m^2 of natural turf (NT) and artificial turf (AT) includes life cycle phases, process or product types, and their respective components. Data are presented per turf type, with associated units and transport distances from Sundsvall to each manufacturing or disposal site.

Lifetime	Artificial turf	Natural turf	Per FU	Distance to Sundsvall [km]
Construction				
Turf field [a]	2.2		kg	2000
PE (fibres) 81 %	1.8		kg	
PP (backing) 11 %	0.3		kg	
Polyurethane (adhesive) 7 %	0.1		kg	
Shock pad, PE foam [b]	3.2		kg	2000
Sand [c]	18		kg	630
Rubber SBR infill (Reused) [c]	13		kg	1300
Soil (Top dress) 80 % sand & 20 % peat [b]		67	kg	12
Fertilizers (N–P–K) [b] [f]		0.05	kg	720
Nitrogen (11 %)		0.006	kg	
Phosphorus (5 %)		0.003	kg	
Potassium (18 %)		0.009	kg	
Seeds [b]		0.04	kg	720
Water		17	litre	
Installation of AT [c]	0.003		hour	
Distribution seeds and fertilizers (diesel) [b]		0.001	litre	
Distribution soil (diesel) [b]		0.3	litre	
Use/Maintenance				
Weekly				
Brushing (diesel) [b]	0.001		litre	
Harrowing (diesel) [b]	0.0003		litre	
Mowing (diesel) [b]		0.001	litre	
Irrigation (water) [d]		13	kWh/ week	
Yearly				
Seed distribution (diesel) [b]		0.001	litre	
Seeds [b]		0.02	kg	730
Aeration (diesel) [b]		0.02	litre	
Wet/dry cleaning (diesel) [b]	0.007		litre	
Dressing distribution (diesel) [b]		0.02	litre	
Dressing (sand) [b]		4.2	kg	
Fertilizer distribution (diesel) [b]		0.0004	litre	
Fertilizers: spring NPK [b] [f]		0.02	kg	730
Nitrogen (20 %)		0.004	kg	
Phosphorus (2.2 %)		0.0005	kg	
Potassium (8.3 %)		0.002	kg	
Fertilizers: long NPK [b] [f]		0.06	kg	730
Nitrogen (26 %)		0.02	kg	
Phosphorus (2.2 %)		0.001	kg	
Potassium (9.1 %)		0.006	kg	
Fertilizers: autumn/ winter NPK [b] [f]		0.02	kg	730
Nitrogen (15 %)		0.003	kg	
Phosphorus (0 %)		0	kg	
Potassium (35.7 %)		0.008	kg	
End of life				
Transport (energy recovery) [e]	5.4		kg	7.9
Turf field [e]	2.2		kg	
PE (fibres) 81 %	1.8		kg	
PP (backing) 11 %	0.3		kg	
Polyurethane (adhesive) 7 %	0.1		kg	
Shock pad, PE foam [e]	3.2		kg	

[a] EPD International (EPD International, 2023).
[b] Assumed data from personal communication with expert.
[c] Assumed data from AT entrepreneur.
[d] Stachowski (2023).
[e] Our own assumption.
[f] Except the amount of NPK there are binders and fillers in the fertilizers (Treinyte et al., 2014).

3.4. Sensitivity and scenario analysis

A sensitivity analysis was conducted to assess how variations in key parameters, such as transport distances, reused or recycled infill and the use of electric maintenance vehicles, influence environmental outcomes. Scenario analysis compared system configurations, with all results calculated over a 10-year lifetime (see Table 3).

3.4.1. Longer and shorter transport distances

Due to the significant weight per m^2 of materials and varying manufacturer locations, transport distances were analysed for their environmental impact during the construction phase, where transport contributes most to tonne-kilometres (tkm). For AT, the longest assumed route was 4000 km (e.g., Lano in Belgium to Sundsvall, Sweden, including carpet and shock pad), with a shorter alternative of 1000 km. For NT, the longest route was 1500 km (e.g., Gothenburg to Sundsvall, including seeds and fertilizers), and the shorter alternative was 400 km. These scenarios help assess the sensitivity of environmental impacts to transport distance variations.

3.4.2. Alternatives of SBR infill

This study assumed that both sand and SBR infill would be reused in the next AT installation. However, as stakeholders and experts note that SBR properties deteriorate over time, some new SBR from shredded tyres may be required. Therefore, a scenario analysis was conducted to compare the environmental impacts of using new SBR versus reused SBR. For the new SBR scenario, the system boundary included the tyre collection, production processes associated with new SBR, the machinery of shredding tires, and transport the infill to the customer. For both new and worn-out reused SBR, incineration was considered as the end-of-life treatment, modelled in Sima Pro with "Waste rubber, unspecified, Europe without Switzerland| treatment of waste rubber, unspecified, municipal incineration | Cut-off, U" from Ecoinvent as output and waste process. The scenario was based on Alongi Skenhall et al. (Alongi Skenhall et al., 2012).

Table 3
– Overview of the factors included in the sensitivity and scenario analyses and the originally selected ones.

Factor	Artificial turf		Natural turf	
	Selected value	Alternatives	Selected value	Alternatives
Distance (km)	2000	1,000, 4000	750	400, 1500
Infill (SBR)	Reused	New	–	–
Machinery used[a]	Diesel tractor[b]	Electric auto carrier[c]	Diesel riding lawn mower[b]	Electric auto mower[d]
Lifetime (years)[e]	10	20, 30	10	20, 30

[a] For AT, the machinery refers to the task of "brushing and harrowing", while for NT refers to the task of "mowing the lawn".
[b] Assumed seasonal diesel use, see Table 2, considering the different machines' efficiencies.
[c] Assumed seasonal energy use of 0.029 kWh/m^2 considering the different machines' efficiencies.
[d] The robot's seasonal energy use was assumed to be 0.014 kWh/m^2.
[e] The effect of change of lifetime due to its significance is incorporated in the main results (Figs. 3–5 in Appendices).

3.4.3. Electric vs diesel maintenance machines

As the data was collected from experts and stakeholders, it was found that most football turfs used diesel-powered vehicles, whereas only a few used electric-powered vehicles. However, it would be of interest to investigate the electric vehicles' influence in the maintenance phase when it comes to environmental impacts. The production and end-of-life phase was not included for the machines since the maintenance phase had the highest impact. In addition to this, the decision for such scenario choices were influenced by input from stakeholders that were interested in how to improve the maintenance phase of the lifetime.

3.4.3.1. Artificial turf – alternatives to brushing and harrowing. For the AT it was decided to test an electric-powered robot instead of the selected diesel-powered tractor in the inventory list (see Table 2), and this tractor served as a tool carrier for both brushing and harrowing. The robot was equipped with a battery pack and an electric motor, which had an assumed energy use of 0.5 kW, according to experts selling such robots. The assumption was based on personal communication with experts. Assuming an efficiency factor of 85 % (Rönnblom et al., 2022) and a charge/discharge efficiency of 90 % (Majeau-Bettez et al., 2011), an additional 10 % is factored into the energy use calculations. The robot's seasonal energy use[1] was assumed to be 0.029 kWh/m^2.

3.4.3.2. Natural turf – alternatives to lawn mowers. The NT have a larger number of electric vehicles for maintenance compared to AT, especially lawn mowers. The most common product on the market is the autonomous electric-powered robot, which was chosen for this analysis to compare with the selected diesel-powered riding lawn mower in the inventory list (see Table 2). The rated power was assumed to be 0.272 kW for the AT with an efficiency factor of 85 % (Rönnblom et al., 2022) and a charge/discharge efficiency of 90 % (Majeau-Bettez et al., 2011); an additional 10 % factored into the energy use calculations were assumed. Moreover, it was assumed that the robot's seasonal energy use was 0.014 kWh/m^2.

4. Results

4.1. Impact assessment

Environmental impacts were assessed using inventory data and SimaPro, with results visualized in Figs. 3–5. These figures present impacts (GWP, PED, AP, EP, TEP, and FEP) over 10-, 20-, and 30-year periods. The AT scenario includes three construction, maintenance, and end-of-life phases; NT includes one construction phase and 30 years of maintenance. All results are based on 1 m^2 of turf.

NT exhibited the highest GWP across all lifetimes, primarily due to AT's end-of-life phase, where 85 % of materials (sand and infill) are reused, reducing the need for new inputs. The remaining 15 % (carpet, fibres, shock pad) undergo energy recovery. Without these end-of-life credits, AT would have the highest impact, as its construction phase is nearly three times greater than NTs over 10 years, increasing six- and nine-fold over 20 and 30 years, respectively. However, NT's maintenance phase contributes more significantly to GWP, with a steeper increase over time. For PED, the difference between AT and NT is less pronounced, though NT consistently requires more energy. The PED trend mirrors GWP, with AT benefiting from reused materials and energy recovery. Overall, AT's construction is more energy intensive, while NT's maintenance phase dominates its environmental impact.

Regarding AP and EP in Fig. 4, the patterns of environmental impacts for each lifetime are almost identical to Fig. 3. It can be observed that NT has the greatest environmental impact across the operational lifespan, primarily due to the significantly negative values in the end-of-life phase. Additionally, the pattern from Fig. 3 is followed, where the impacts from the construction phase for AT are significantly higher than for NT for both AP and EP, while the impacts from the maintenance phase are considerably more for NT than AT for both AP and EP. For both AP and EP, a strongly increasing trend per lifetime for NT compared to AT is also evident.

For the final two environmental impacts, TEP and FEP in Fig. 5, the same pattern from Figs. 3 and 4 continues, where the results indicate that NT has the greatest environmental impact for TEP and FEP across the operational lifespan compared to AT. These results are also influenced by the negative values due to the recycling of sand and infill materials while a new AT field needs to be manufactured. The construction phase for AT has a significantly higher environmental impact than for NT, but at the same time, the impact from the maintenance phase for NT is higher than for AT. Similar trends can be observed in Fig. 5, where NT increases more significantly between each lifetime period.

NT demonstrated the highest environmental impacts across all categories, primarily due to its intensive maintenance phase, which involves six processes (transport, mowing, fertilizing, seeding, dressing, and aeration) and four material inputs (fertilizers, water, turf seeds, and sand). These activities require substantial diesel use and contribute significantly to emissions, particularly in AP and EP. In contrast, AT maintenance involves only three processes (brushing, harrowing, and deep cleaning) and use less energy. However, AT exhibits the highest impacts during the construction phase due to the energy-intensive production of plastic-based components (fibres, carpet, and shock pad), which rely on crude oil extraction. Notably, 85 % of AT materials are

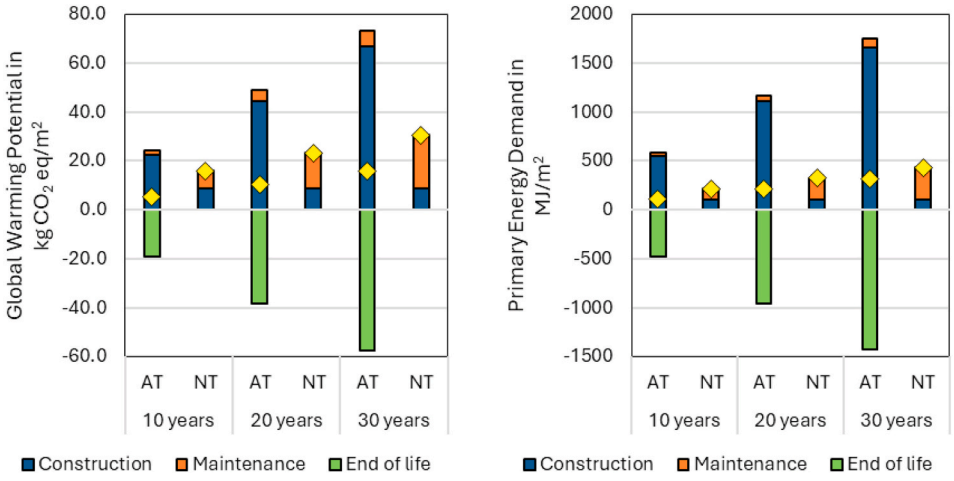

Fig. 3. GWP in kg CO2 eq/m^2 turf (left) and PED in MJ/m^2 turf (right) for the reference case. The blue bars represent the construction phase, the orange bars represent the maintenance phase, the green bars represent the end-of-life phase, and the yellow diamonds represent the total LCA impact.

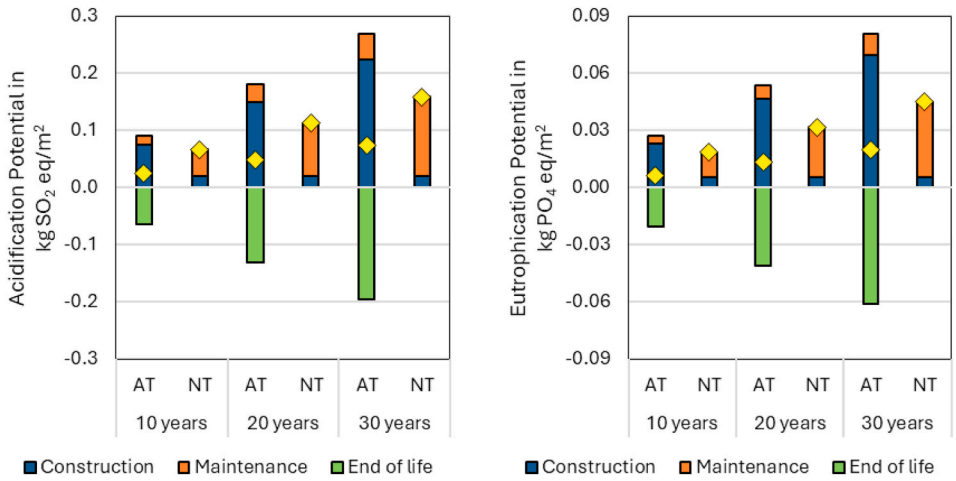

Fig. 4. AP in kg SO_2 eq/m^2 turf (left) and EP in kg PO_4 eq/m^2 turf (right) for the reference case. The blue bars represent the construction phase, the orange bars represent the maintenance phase, the green bars represent the end-of-life phase, and the yellow diamonds represent the total LCA impact.

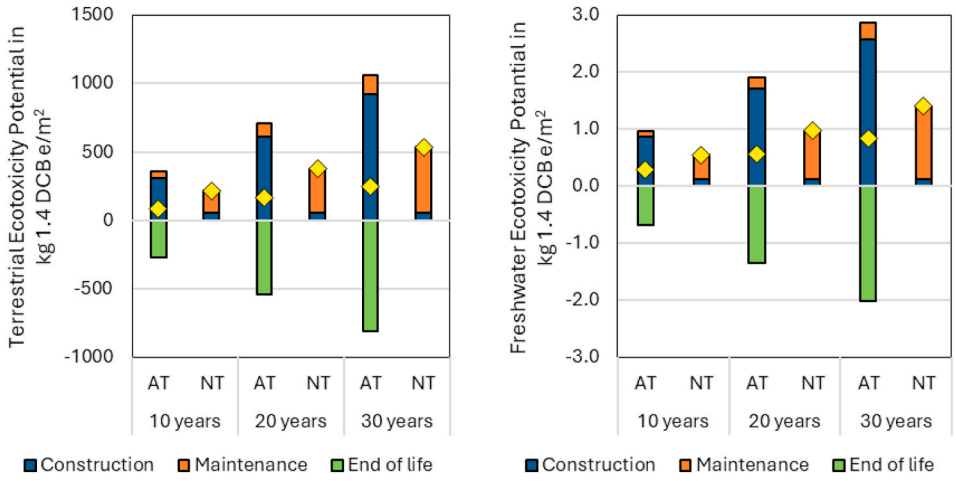

Fig. 5. TEP in kg 1.4 DCB e/m^2 turf (left) and FEP in kg 1.4 DCB e/m^2 turf (right) for the reference case. The blue bars represent the construction phase, the orange bars represent the maintenance phase, the green bars represent the end-of-life phase, and the yellow diamonds represent the total LCA impact.

reused at end-of-life, reducing the need for new sand and infill, and 15 % of the AT (plastic carpet, fibres and shock pad) ends up as energy recovery. Without this recycling, AT would surpass NT in environmental impacts across the operational lifespan. Thus, material recovery is essential to minimizing AT's overall environmental footprint. Additional information regarding this process is available in the Supplementary Materials.

4.2. *Sensitivity and scenario analyses*

A sensitivity and a scenario analysis were conducted to assess the robustness of the results. Three parameters were tested: variations in transport distances for both AT and NT, the differences between reused and recycled infill, and the use of alternative electric tool carriers as maintenance machines.

4.2.1. *Longer and shorter transport distances*

Figs. 6 and 7 presents sensitivity analysis results for transport distance variability based on manufacturer location. For AT, the baseline distance was approximately 2000 km, with 1000 km and 4000 km representing shorter and longer alternatives. For NT, the selected distance was around 740 km, with 400 km and 1500 km used as comparative values. All results reflect a 10-year lifetime perspective.

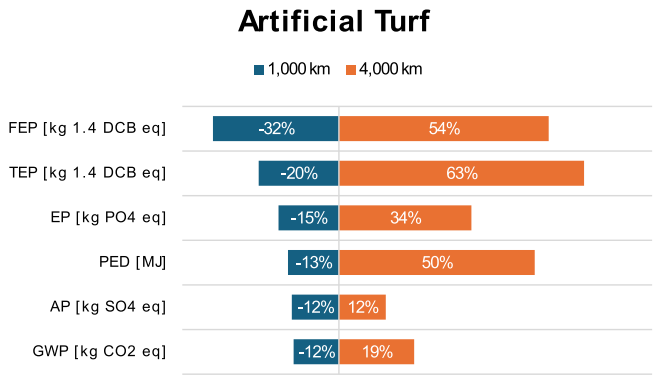

Fig. 6. Environmental impacts are visualized based on various distances from the selected points of AT, considering both shorter and longer distances.

Fig. 6 shows that PED, TEP, and FEP are the most affected impact categories for AT, particularly when transport distances double from the baseline of 2000 km. For NT (Fig. 7), TEP increases by 57 % under the same condition. Notably, TEP has the most influenced impact in both turfs. These findings underscore the significant influence of transport on environmental outcomes and suggest that sourcing locally produced

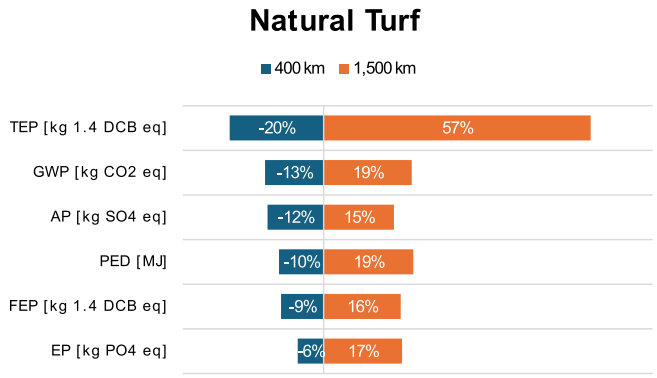

Fig. 7. Environmental impacts are visualized based on various distances from the selected points of NT, considering both shorter and longer distances.

turfs can substantially reduce impacts, especially for AT.

4.2.2. Alternatives of SBR infill

The processes included for the new SBR infill were tyre collection, cutting, granulation, and transport of granulation to AT. The total energy use from production of 13.3 kg (amount of SBR infill per FU, see Table 2) infill by electricity (cutting and granulation) resulted in 21.8 MJ/m^2 while production and delivery by diesel (cutting and transport (one way loaded)) resulted in 6.8 MJ/m^2. For end-of-life treatment of worn-out SBR infill 13.3 kg was incinerated (both new and reused).

The results presented in Table 4 demonstrate that the environmental impacts associated with using new SBR, as opposed to reused SBR, differ significantly. For all assessed impact categories, the use of new SBR results in values at least two times higher than those observed for reused SBR. Among these, the GWP and PED exhibit the most pronounced differences.

4.2.3. Electric vs diesel maintenance machine

4.2.3.1. Artificial turf – alternatives to brushing and harrowing. The sensitivity analysis compared diesel-powered maintenance using SimaPro data with an electric alternative—an autonomous robot consuming 0.029 kWh/m^2. Diesel use (tractor) is detailed in Table 3. Results, based on a 10-year lifetime, highlight the environmental implications of transitioning to electric maintenance equipment.

Overall, the results in Table 5 demonstrated the significant impact of the electric robot compared to the diesel tractor across all environmental impacts, with AP and EP showing the most substantial reduction at 64 % and 57 % respectively. The least impact, with 27 % reduction, resulted from PED. It can be concluded that a diesel tractor is not an optimal solution for routine weekly brushing and harrowing; instead, an electric alternative such as an autonomous carrier is preferable.

4.2.3.2. Natural turf – alternatives to lawn mowers. An additional analysis compared two mowing alternatives during the maintenance phase: a diesel riding mower and an electric auto mower. Results are shown in Table 6. Diesel consumption is detailed in Table 3, while the electric mower's energy use was estimated at 0.014 kWh/m^2. All results are based on a 10-year lifetime perspective.

In the analysis of the AT maintenance case, the transition to an electric machine result in a relatively modest improvement. As shown in Table 6, all environmental impact categories exhibit reductions, with TEP and FEP each decreasing the most by 18 %. PED shows the smallest reduction, at only 7 %. The results indicate that the environmental benefits of switching from a diesel riding lawn mower to an electric autonomous mower are relatively modest, particularly when compared to the differences observed in Table 5.

In summary, the sensitivity and scenario analyses indicate that investing in locally produced turf, particularly AT, results in lower environmental impacts. Key contributing factors include transport distance, as well as the volume and weight of the products. Notably, electric alternatives are significantly more suitable for maintaining AT compared to NT. This may be attributed to the operational optimization of tractors versus riding lawn mowers, despite both being powered by diesel. Tractors are designed as multifunctional machines, whereas riding lawn mowers are specialized solely for grass cutting.

5. Discussion

The LCA of NT and AT revealed consistent trends across all environmental impacts and was where NT was found to be the type that gave rise to most negative impacts. AT exhibited the highest environmental impacts during the construction phase, primarily emanating from material production. Conversely, NT required substantial labour, processes and materials during the use and maintenance phase, leading to high environmental impacts associated with diesel and fertilizer usage. In the end-of-life phase, AT was assumed to have its sand and infill materials reused, while the turf carpet, backing and shock pad were incinerated for energy recovery. It is noteworthy that, without the material recycling process, AT would have had the highest environmental impact. Therefore, ensuring both material recycling and energy recovery during the end-of-life management of AT is crucial for minimizing environmental impacts and promoting sustainable resource use.

The largest emitter during the construction phase was AT, for which the production of PE and PP played a significant role. This finding is supported by Marczak (2022), who identified PE and PP as the most energy-intensive polymers during production in her study of six different polymers.

In the use and maintenance phase, NT involved six processes distributing four different materials annually, compared to three processes for the AT, which Barnes and Watkins (Barnes et al., 2022) highlight as a pro for AT, while NT is critiqued for this (Elnaggar, 2024). Additionally, Zeilerbauer et al. (2024) emphasize that the use of diesel in machinery and using of fertilizers for NT significantly impacts the environment, suggesting that reducing these inputs could improve environmental outcomes. To compare with another type of sport using similar NT, a study by Tidåker et al. (2017) analysed two Swedish golf courses using LCA. The study found that the most energy-using process was mowing the course with a diesel mower. Another significant finding, also highlighted in this paper, was the high environmental impact of fertilizer manufacturing, for which Tidåker et al. (2017) found that nitrogen fertilizers, especially, had the most substantial influence.

In the end-of-life phase, it was assumed that the AT field reused sand and rubber (SBR) infill, along with energy recovery through incineration of the carpet, backing and shock pad. This step was found to be crucial for reducing the environmental impacts of AT. Most other studies have not investigated this disposal process, instead focusing on the leakage of microplastics from the turf into the environment (de Haan et al., 2023; Sundan et al., 2025), or solely on the disposal of rubber infill (Lu et al.,

Table 4
Environmental impacts are visualized based on the selected reused SBR compared with new SBR (from shredded tyres).

Infill (SBR)	GWP [kg CO_2 eq/m^2]	PED [MJ/m^2]	EP [kg PO_4 eq/m^2]	AP [kg SO_4 eq/m^2]	TEP [kg 1.4 DCB eq/m^2]	FEP [kg 1.4 DCB eq/m^2]
Artificial turf						
Reused (selected)	5.2	100	0.0065	0.025	83	0.28
New (alternative)	23 (342 %)	585 (485 %)	0.025 (277 %)	0.082 (227 %)	318 (283 %)	0.96 (244 %)

Table 5
– Environmental impacts are visualized from the selected tool carrier of this study compared with the electric alternative, an electric-powered robot. The tasks for both tool carriers include the weekly and monthly brushing and harrowing.

Task: Brushing and harrowing	GWP [kg CO_2 eq/m^2]	PED [MJ/m^2]	EP [kg PO_4 eq/m^2]	AP [kg SO_4 eq/m^2]	TEP [kg 1.4 DCB eq/m^2]	FEP [kg 1.4 DCB eq/m^2]
Artificial turf						
Diesel tractor (selected)	5.2	100	0.0065	0.025	83	0.28
Electric auto carrier (alternative)	3 (−42 %)	76 (−27 %)	0.0028 (−57 %)	0.009 (−64 %)	37 (−55 %)	0.19 (−32 %)

Table 6
– Environmental impacts are visualized from the selected tool carrier of this study compared with the electric alternative, an electric-powered robot. The tasks for both tool carriers include the weekly lawn mowing.

Task: Mowing the lawn	GWP [kg CO_2 eq/m^2]	PED [MJ/m^2]	EP [kg PO_4 eq/m^2]	AP [kg SO_4 eq/m^2]	TEP [kg 1.4 DCB eq/m^2]	FEP [kg 1.4 DCB eq/m^2]
Natural turf						
Diesel riding lawn mower (selected)	16	210	0.018	0.067	220	0.55
Electric auto mower (alternative)	15 (−8 %)	190 (−7 %)	0.016 (−11 %)	0.059 (−12 %)	180 (−18 %)	0.45 (−18 %)

2021; Xie et al., 2022). However, one study by de Bernardi and Waller (de Bernardi and Waller, 2022) highlighted this issue, discussing the knowledge of owners and stakeholders regarding the disposal process. Some turf owners (among the stakeholders of this study) opted to pay for the transport of AT to dedicated recycling facilities. Some organizations facilitated the reuse of ATs by transferring them to other facilities with lower demands on the quality of the pitch. This practice is particularly feasible for ATs used by professional clubs, for which more frequent replacements are necessary to meet competition certification standards from FIFA, called FIFA Quality Pro (FIFA and FIFA Quality Programme For Football Turf, 2024). Additionally, some owners believed that ATs were incinerated for energy recovery, although there was uncertainty regarding this practice. These findings from de Bernardi and Waller (de Bernardi and Waller, 2022) seems to align with the responses obtained from experts and stakeholders during personal communication within this paper that was done during the data collection and validation phase of the results, indicating a value gap in the disposal process.

The reason NT provides the most negative environmental impacts is due to its use and maintenance phase, where significant amounts of diesel are consumed for mowing, aerating, fertilizing and topdressing. Fertilization, applied three times per year, has a particularly high energy use during production and adds to the impact of various factors during the use and maintenance phase, including acidification and eutrophication but also terrestrial and freshwater toxicity. Additionally, the production of AT significantly impacts the environment due to its use of raw oil and high energy use in the manufacture of carpet, backing and shock pad. The assumption that the entire AT, including sand and infill, can be reused and energy recovered after 10 years of use results in a lower overall impact compared with NT. Furthermore, discussions with suppliers of entire AT systems indicate that the shock pad may have a lifetime of up to 20 years, depending on usage conditions. However, for the purposes of this study, it was conservatively assumed that the shock pad is replaced concurrently with the AT carpet. If, instead, the shock pad was to be replaced only every second AT lifetime, the total environmental impact would be further reduced. This study underscores the importance of reuse and recycling the entire AT in the end of its lifetime.

There are several further lines of research for both NT and AT that warrant further investigation. Both field types involve the transport of heavy weight materials, with distances that remain uncertain according to the experts and stakeholders. While materials for NTs are produced in Sweden, ATs are predominantly manufactured in other countries, notably in Europe and China. Consequently, transport distance could significantly lower the environmental impacts if producers were locally situated. The sensitivity analysis demonstrated that transport distance is a critical factor, as materials for NT were assumed to travel shorter distances compared with AT.

The uncertainty regarding whether SBR infill is replaced during each AT renewal prompted the inclusion of a scenario involving new SBR derived from shredded tyres. A scenario analysis, primarily informed by a single study and supplemented with proprietary modelling conducted in SimaPro, highlighted the critical importance of reusing existing infill. The findings suggest that new SBR should only be utilized when reuse is not feasible, to minimize environmental impacts. It should be noted that the study by Alongi Skenhall et al. (Alongi Skenhall et al., 2012) utilized 6.5 kg SBR infill per FU, which is only half the amount of SBR infill per FU applied in the present study. Notably, alternative virgin rubber infills such as EPDM and TPE exhibited significantly higher GWP, with EPDM and TPE showing approximately 10-fold and 35-fold increases, respectively, compared to new SBR showed by Alongi Skenhall et al. (Alongi Skenhall et al., 2012).

Previous studies, along with this paper, identified diesel consumption as a major contributor to high environmental impacts during the use and maintenance phase. To address this, a scenario analysis was conducted, substituting diesel-powered machines (mowers for NT and tractors for AT) with electric autonomous robots for weekly maintenance. This substitution resulted in an average reduction of all environmental impacts by 46 % units for the electric robot maintaining an AT, while for NT, there was a lower reduction of 10 % units. Turf owners in Sweden predominantly use tractors for brushing and harrowing AT, indicating that employing electric autonomous robots could reduce the environmental impacts over a 10-year lifetime of use and maintenance by 50 %. However, consideration must be given to how employees will be affected by this change, despite its potential to save money, time, and reduce environmental impacts. This could include using more cost-effective options such as electric operated lawn mowers or other suitable electric vehicles for brushing and harrowing.

This study focused on a 24-week period from April to October in Sundsvall, Sweden, corresponding to the operational window during which NT can be utilized. This timeframe was selected to ensure a fair and consistent comparison between the two turf alternatives. However, there remains a significant need for further empirical research that evaluates actual annual playing hours to establish a more comprehensive and realistic basis for comparison.

6. Conclusions

By analysing the environmental impacts, from a life cycle perspective, of artificial and natural turf, this paper has provided new insights into the quantity and sources of emissions of each turf type and remains one of the first of its kind related to the Nordic climate. This study presented a life cycle assessment of 1 m^2 artificial and natural football turfs in Nordic climates, evaluating their environmental impacts such as global warming potential, primary energy demand, acidification potential, eutrophication potential and ecotoxicity potential across construction, use, maintenance, and end-of-life phases over lifetimes of 10, 20 and 30 years. Natural turf exhibited the highest overall environmental impacts over the operational lifespan, e.g. the global warming potential and primary energy demand were 30.6 kg CO_2 eq/m^2 and

431.5 MJ/m^2, while the artificial turf reached 15.6 kg CO_2 eq/m^2 and 312.5 MJ/m^2. During the construction phase, artificial turf generated significant emissions, mainly from material production. In the use phase, natural turf showed the greatest impacts due to diesel consumption and fertilizer application. At the end-of-life stage, artificial turf's sand and infill were reused, while the turf carpet and shock pad were incinerated for energy recovery. Results suggest several practical solutions to mitigate the turfs' environmental impact. Firstly, the most critical measure is the recycling of AT in the end-of-life phase. Without this process, results clearly indicate that AT has the highest environmental impacts. Secondly, optimizing the maintenance phase for both field types is essential. Given the numerous materials and processes required for NT, any optimization could reduce environmental impacts. For AT, weekly maintenance should not involve using a diesel-powered tractor for brushing and harrowing; instead, an electric alternative, such as an autonomous robot, should be considered. Additionally, the study has incorporated sensitivity and scenario analyses to illustrate how various factors interact, offering recommendations to turf owners and other relevant stakeholders on how to reduce their environmental impacts.

Future research should explore alternatives to produce and manufacture AT, given its significant environmental impacts. This study focused on the period from April to October, as NT cannot be used from October to April in the Nordic climate, whereas AT allows for year-round play. However, with the upcoming ban on rubber infill for AT effective from 2031, questions arise regarding the performance of bio infill substitutes, particularly in freezing conditions. Therefore, future research should include and quantify the utility and performance of both field types under various climatic conditions during the whole year. Furthermore, employing a fully probabilistic framework, such as Monte Carlo simulation, would enhance the robustness of the findings by systematically propagating uncertainties, thereby enabling a more comprehensive evaluation of result variability. Additionally, given the significant environmental impacts associated with fertilizer production and use, as identified in recent studies and this paper, conducting an audit or interview study would be valuable and could aim to investigate the knowledge foundation of facility managers, and assess the efficiency of fertilizer usage, for example. Lastly, it is essential to investigate and audit the types of maintenance machines used at each facility, as this paper has demonstrated that changes in this area can significantly reduce environmental impacts.

CRediT authorship contribution statement

Mikael Säberg: Writing – original draft. **Emma Lindkvist:** Writing – review & editing. **Roozbeh Feiz:** Writing – review & editing. **Patrik Thollander:** Writing – review & editing.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Emma Lindkvist reports financial support was provided by The Kamprad Family Foundation. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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During the preparation of this work the author(s) used a paid service together with Microsoft Copilot in order to check grammar and language. After using this tool/service, the author(s) reviewed and edited the content as needed and take(s) full responsibility for the content of the published article.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.cesys.2025.100369.

Data availability

Data will be made available on request.

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