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Biodiversity burdens in Spanish conventional and low-impact single-family homes

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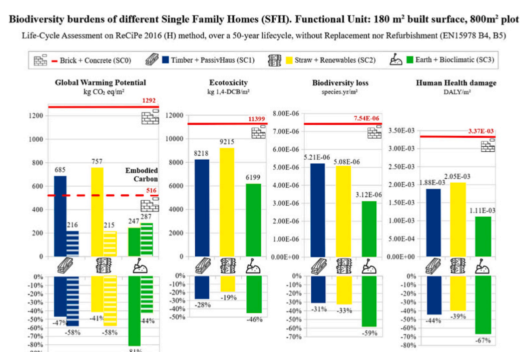
HIGHLIGHTS

- Damage of single-family houses on biodiversity and human health is assessed in a 50 year lifecycle.
- Terrestrial ecotoxicity midpoint impacts weight more than CO_2eq emissions to the atmosphere.
- Timber, straw, or rammed earth constructions cut impacts of conventional brick houses by half.
- The Spanish stock of single-family houses drives yearly 6.052 species extinct in a 50 year lifecycle.

GRAPHICAL ABSTRACT



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ABSTRACT

Biodiversity loss caused by housing is not a well-defined sector of environmental impact. This research quantifies effects on biodiversity of an average Spanish Single-Family House (SFH) with 180 m^2 of built surface. The current Spanish SFH stock GWP amounts to 1.16 Gt CO_2eq in a 50-year life cycle, 40 % of which is embodied in the building materials and the 60 % are emissions due to the use of the building. This stock also impacts with 10.2 Gt 1,4-DCB the land, water and human health. SFHs also drive 6052 species extinct in a 50 year life cycle, and account for 3.03 M years of life lost due to premature death or lived with a disability. Divided by the 16 M people living in Spanish SFHs, each one lost 0.19 years of their lives (68.1 days) due to their home's impacts on human health.

The article compares a reference conventional building against three low-impact cases, to understand how different building techniques and materials influence environmental outcomes that keep biodiversity loss the lowest possible. Scenarios include a standard brick and concrete house as Scenario 0 (SC0, Base), a timber Passivhaus as Scenario 1 (SC1), a straw-bale house with renewable energies as Scenario 2 (SC2), and an earth bioclimatic house as Scenario 3 (SC3). An initial Global Warming Potential (GWP) analysis was performed to relate previous building Life Cycle Assessment (LCA) studies with biodiversity metrics. Three main biodiversity

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metrics; ecotoxicity (as midpoint indicator), biodiversity loss and damage to human health (both as endpoint indicators) have been considered.

Compared to SC0 with 1292 $kgCO_2$-eq·m^{-2} (516 embodied) of GWP, we found that SC1 emitted −47.0 % of that, SC2–41.4 % and SC3–80.9 %. Concerning ecotoxicity, where SC0 has 11,399 kg 1,4 DCB, the results are −27.9 % in SC1, −19.2 % in SC2, and −45.6 % in SC3. Regarding biodiversity loss, where SC0 has 7.54 E^{-06} species.yr·m^{-2}, the impacts are −30.9 % in SC1, −32.6 % in SC2, and −58.6 % in SC3.

Human health damage in SC0 being 3.37 E^{-03} DALY, has been reduced in the timber home (SC1) is −44.2 %, of the Straw SFH (SC2) −39.2 %, and of the earth house (SC3) −67.1 %.

This article shows that with current existing technological solutions GWP could be reduced in −80.9 %, ecotoxicity in −45.6 %, biodiversity loss in −58.6 % and human health in −67.1 %. Spanish Single-Family Houses built in timber, earth or straw-bale are real alternatives to current cement traditional building.

1. Introduction

The Kunming-Montreal Global Biodiversity Framework, agreed at the United Nations Biodiversity Conference COP15 on Biological Diversity, on the establishment of 4 goals and 23 targets to be achieved by 2050. These include the restoration of the integrity, connectivity and resilience of all ecosystems, the reduction to one-tenth of the extinction rate and risk of all species, the safeguard of genetic diversity, the sustainable use of biodiversity and ecosystem functions and services, and the progressive and universal closing of the biodiversity finance gap of \$700 billion per year. Its target 12 specifies the need to ensure biodiversity-inclusive urban planning and buildings. Its target 19/f calls for “Mother Earth Centric” actions to restore ecosystems at every human activity, including buildings (CBD, 2022). The EU's Biodiversity Strategy for 2030 plans to protect nature, and reverse ecosystems' degradation. It aims at putting Europe's biodiversity on a path to recovery by 2030 and is a core part of the European Green Deal. It builds resilience to threats such as the impacts of climate change, forest fires, food insecurity or disease outbreaks. It extends Natura 2000 areas and launches an EU Nature Restoration Plan to better respect nature in public and business decision-making (DG Env EC, 2021). Target 14 of the EU Biodiversity Strategy urges cities with at least 20,000 inhabitants to have an ambitious Urban Greening Plan following a guidance document (CIRCABC, 2022) and an online Urban Greening Platform (DG Env EC, 2021). Some countries, as Spain, have already transposed it into their own regulations (MITERD, 2021), identifying 23 ecosystem services in green urban infrastructures, relating actions to regulations on building refurbishment and urban regeneration, prompting ecological landscaping in building and urban design, limiting construction works in sensitive areas and avoiding nature fragmentation.

However, according to the United Nations Organization, (DESA, 2018) estimations on population growth speak of 9700 M people by 2050, 68 % of them living in cities, of which 43 megacities will host >10 M. The construction of new 25 M km of roads (60 % more than in 2010) and 335,000 km of railroads are expected in 2050, 90 % of which on greenfield. Also, related Sustainable Development Goals (SDG) 14 “Marine life” and 15 “Terrestrial ecosystems” experience direct threats, and SDG 2 “Nutrition” and 6 “Clean water”, indirect. Insufficient integration of SDG 13 “Climate change” and those containing ecotoxicity and overexploitation issues, SDG 6 and 12, deter the Goals from reaching expected results (CBD, 2020). The “State of nature in the EU” report, based on the Birds (2009/147/EC) and the Habitats (92/43/EEC) directives, the Natura 2000 network and the targets 1 and 3 of the previous EU 2020 Biodiversity Strategy, confirm continuous worsening of species status, from 32 % in 2012, to 39 % in 2018, and 9 % fewer wintering birds in the same period. Habitat conservation worsened too (75 % in 2012, 81 % in 2018), with only 15 % of the 233 European habitats well preserved. The Natura 2000 network, despite some positive impacts, has not achieved its potential effectiveness. As a result, there is a 12 % conservation gap for habitats, 20 % for bird species, and 2 % for non-bird species. Also 31 % of forest habitats have a bad conservation status. (EEA, 2020) concludes that biodiversity in the EU continues to decline and faces deteriorating trends from changes in land and sea use, overexploitation and unsustainable management practices, as well as water regime modification, pollution, invasive alien species and climate change.

The Intergovernmental Platform on Biodiversity and Ecosystem Services focuses on strengthening the science-policy interface for the conservation of biodiversity and ecosystem services, long-term human well-being and sustainable development. Its European region Assessment Report (IPBES, 2018a) admits that nature's contributions to people are under threat due to the continuing loss of biodiversity, that European biodiversity is in continuous strong decline, and that progress towards healthy ecosystems is insufficient. Land use change is the major direct driver of the loss of both biodiversity and ecosystem services. Trends in natural resource extraction, pollution and invasive alien species lead to biodiversity decline. Economic growth is not decoupled from environmental degradation, preventing widespread achievement of goals similar to and including the SDG. Its Assessment Report on Land Degradation and Restoration (IPBES, 2018b) warns that combating land degradation and restoring it is an urgent priority to protect biodiversity and ecosystem services vital to all life on Earth, and to ensure human health. Human-induced Earth's land degradation negatively impacts the health of at least 3.2 Bn people, pushes the planet towards a 6th mass extinction, and costs >10 % of annual global GDP. Land degradation and climate change are likely to force up to 700 M people to migrate by 2050. 97 % of land (excluding Antarctica) and 87 % of oceans have been modified by human activities. 83 % of wild mammal biomass and 50 % of plants have been lost. Livestock and humans now account for nearly 96 % of all mammal biomass. Climate change increasingly interacts with these processes (IPBES, 2021). Moreover, the Workshop Report on Biodiversity and Pandemics concludes that 70 % of emerging diseases like Ebola or Zika, and all known pandemics like AIDS or COVID-19, jump from microbes of animal origin. It is believed that there are 1.7 M viruses yet to be discovered in animal hosts, 52 % of which could have the capacity to infect humans. Land use change is a global driver of pandemics and caused the emergence of over 30 % of the new diseases since 1960 (IPBES, 2020).

The world's global built-up area is projected to double by 2060; an extra 230 Bn m^2, equivalent to the size of New York City every month (Adams et al., 2019). In 2021, the building industry global emissions reached 13.6 Gt CO_2eq and its energy consumption 37,500 GWh (UNEP, 2022). Housing is responsible for 22 % of the industry's energy demand and 17 % of the related CO_2eq emissions. In Europe, an estimated 97 % of the building stock is not efficient enough to comply with the Paris Agreement. To limit carbon emissions, Europe is leading the way in terms of carbon regulations and building benchmarks (Izaola et al., 2022), but the importance of liveable and biodiverse cities is still underestimated (Botzat et al., 2016). European limits on energy-related emissions (European Commission, 2021) for Spain, aim for a Class A of 6.8 kg CO_2-eq·m^{-2}·y^{-1}, although current averages are Class E, between 26.4 and 59.1 kg CO_2-eq·m^{-2}·y^{-1}. Current average Global Warming Potential (GWP) baselines for residential buildings of 1298 kg CO_2-eq·m^{-2} over a 50-year life cycle have been suggested for Europe, and of 1240 for Spain (Izaola et al., 2023).

The goal of this research is to propose impact metrics on biodiversity loss (1) and human health (2) of the average Spanish Single-Family House (SFH) and its low-impact variations. The average Spanish SFH has been characterized by a 180 m^2 home on an 800 m^2 plot in Madrid. This base building has been compared to three other SFH within the same climate zone (D3): a Cross-Laminated Timber (CLT) house, a straw bale house, and a rammed earth SFH. This research suggests that midpoint terrestrial ecotoxicity impacts create more damage than global warming emissions. Recognizing the importance and contribution of midpoint GWP data to understand climate change, the authors suggest looking at endpoint areas as well, in order to understand ecosystem quality loss affecting both humans and all other species. The overall habitability of the planet is at stake, but humans might not realize this if they only look at greenhouse gas emissions to the atmosphere, or the building industry by limiting only GWP. Instead, this article gives figures of how many species disappear and how much a human life is shortened due to buildings. The industry's increasing responsibility to comply with the Paris Agreement by implementing specific GWP reduction measures could prompt other biodiversity protection agreements by specifically reducing harm to humans and other species. This article quantifies the extent to which this reduction is achieved by choosing known low-impact building materials and techniques. It is structured with an initial literature review and a subsequent section to describe the methodological approach. The results section shows detailed figures on the proposed metrics. At the end, the discussion and conclusions comment on these results in the light of the studies reviewed, including some recommendations for interpreting results, raising awareness, clarifying limitations and suggesting further research.

2. Literature review

The scientific study of biodiversity loss as proxy for Ecosystem Damage (ED) (1) and human life expectancy reduction (2), caused by buildings is a new field of analysis following the GWP of the industry (Bahramian and Yetilmezsoy, 2020). Initial impacts within the construction site (in-situ) and off-site (ex-situ) in building components such as roofs are analyzed, showing that an extensive green roof loses 35 % less biodiversity (9.34E^{-07} against 1.43E^{-06} species.yr) than a conventional one, and that ex-situ biodiversity impacts are 10 times higher than in-situ (Brachet et al., 2019). Building materials have also been compared in terms of their impact on Human Health (HH). For instance, timber has 95 % less effects on HH (1.26E^{-06} vs. 2.98E^{-05} DALY) than ceramic tiles (Shi et al., 2022). Technological innovation in the industry offers some positive results, as is the case with the latest generation of photovoltaics (PV). For instance, Perovskite panels cause 68 % less HH damage (4.56E^{-07} vs. 1.43E^{-06} DALY) than polycrystalline (Zahedi et al., 2022). HH damage and ecotoxicity of rooftop PV is also analyzed throughout Europe with big differences due to location (Martinopoulos, 2020). Another study compares HH and ED impacts of a renovated building and new ones in timber frame, CLT and conventional concrete. Although renovation is clearly the best option (39.4 % HH and 36.3 % ED impacts than that of the concrete building), both timber solutions have 15 % less HH impacts than the concrete one. However, it is inconclusive in terms of ED impacts (Ryberg et al., 2021).

Although the damage pathways between Midpoint impacts and Endpoint protection areas are well defined and interconnected in methods such as ReCiPe 2016 (Huijbregts et al., 2017), sciences still address climate, biodiversity and social impacts separately, despite scientists claiming for an integrated approach to overcome the multiple crises (Pörtner et al., 2023). ReCiPe points to damage to terrestrial species with 6 pathways, followed by damage to freshwater species and to HH with 4 pathways. These three damages share GWP as main precursor. However, their dependencies are not sufficiently studied. For instance, only two studies were found that concomitantly quantify aspects of pollinator health and HH (Garibaldi et al., 2022), although their nutritional and medicinal contribution is indisputable. It is necessary to dive deeper into the pollutants emitted by building materials (Park et al., 2016), (Bhoonah et al., 2023), their life cycle eutrophication (Kobetičová and Černý, 2019) and toxicity effects (Rey-Álvarez et al., 2022), to find the connections between human and ecosystem health. ReCiPe clarifies this by defining Endpoints related to three critical areas of protection. Human health is represented by the years that are lost or that a person is disabled due to a disease or accident, with the metric "DALY" (disability-adjusted life years). Ecosystem damage is measured by the time-integrated loss of local species, "species year". The third one, out of the scope of this article is resource scarcity, accounted in dollars (US$), which represents the additional costs involved in future mineral and fossil resource extraction (Huijbregts et al., 2017).

As already exemplified, insect decline is a proxy indicator of biodiversity loss or ED. Insects constitute the world's most abundant animal group and provide critical ecosystem services. The current proportion of insect species in decline (41 %) doubles that of vertebrates (20 %). Every year, 1 % of all insect species are lost, and the decline in biodiversity accounts for an annual loss of 2.5 % of the world's biomass. Decline is similar in tropical (45 %) and temperate regions of the world (continental Europe, 44 %). Causes of insect decline include habitat change as the main driver (49.7 %), followed by pollution (25.8 %). Habitat change derives from land transformation to provide housing, mobility, industry, or agriculture. Agriculture causes 24 % of insect decline, urbanization 11 %, and deforestation 9 %. In terms of pollution, herbicides, insecticides and fungicides cause 13 % of the decline, fertilizer inputs 10 %, and urban and industrial sewage and landfill leachates 3 %. Fertilizers and sewage also cause eutrophication and acidification with direct toxic effects and indirect support of biological factors as parasites and pathogens. Likewise, invasive species are favored by climate change and urbanization (Sánchez-Bayo and Wyckhuys, 2019). There are, however, studies arguing that low-density urbanization with integrated landscaping has less impact on pollinators than intensive agriculture (Wenzel et al., 2020).

At ecosystem level, building impacts change over the years, depending on factors such as location, building type, and species' specificity. In terms of bird deaths, it is estimated that 988 M birds die annually in the USA by collision with buildings (Loss et al., 2012). Regarding habitat loss and fragmentation, several studies assess the negative effects of urbanization on forests (Zhou et al., 2017) and ecosystems (Liu et al., 2016). Buildings and infrastructures can generate light pollution, disrupting the behavior and migratory patterns of flying and swimming species. It drives moth (Boyes et al., 2021) or bat decline (Haddock et al., 2019), turtle disorientation (Silva et al., 2017), and in general, reduces fish abundance (Bolton et al., 2017). Likewise, noise pollution from buildings above 40dBA can disrupt the communication and breeding behavior of mammals, birds and amphibians (Shannon et al., 2016). Overall, studies highlight the importance of considering biodiversity and ecological impacts in the design, construction and management of buildings.

At urban level, there are numerous calls for defining urban biodiversity, and connecting it to urban planning, but few examples like the Rotterdamm "Green Metamorphosis Plan", the Edmonton network of biodiversity corridors, or the more recent planning actions in Montreal and Melbourne explicitly address and deliver on biodiversity conservation (Oke et al., 2021). However, approaches for cities to play a relevant role in addressing global extinction are on the agendas and include citizen participation, shared use of urban gardens, strengthening ecosystem communities, creating refugia for species, and broadening the geographic and taxonomic focus. Again, some pioneers like the 260 German municipalities network "Kommbio", the 11 Southafrican cities under a wetland protection program, the GUBIC consortium or the UWIN partnership (Knapp et al., 2021) should be highlighted. 34 specific attributes that a biodiverse city should have, according to (Nilon et al., 2017), include baselining and monitoring goals on local species protection, habitat management, constructing bio-swales, green roofs, green streets, rain gardens, yards and other green infrastructures using nature-based solutions, more taxa and ecosystem space, improvement of water quality and flood retention, removing air, light and noise pollution; improvement of urban heat islands, authorization of urban agriculture, etc.

Despite cities hardly occupy 3 % of global land area, they host 5 Bn people who exploit 82 % of the land and oceans. However, cities can provide habitat and ecosystem services to a much wider community of species. For instance, 25 % of unfragmented urban area dedicated to Atlantic forest in the proper climate zones for 65 years can achieve 80 % of the biodiversity found in mature forests, albeit they require more than a thousand years to reach endemic levels (40 % of species) (Pedersen Zari, 2019). A built environment incorporating biodiversity would improve the planet's ability to adapt to climate change, air quality, flood mitigation and the overall health and well-being of people, thus contributing to reach the SDGs (Opoku, 2019).

At building level, typology, occupancy and climate zone are relevant factors to take into account when considering environmental impacts of SFH. Lavagna et al. (2018) provide figures for the total annual (related to 2010) EU-27 LCA impacts in relation to housing on 15 EN15978 impact categories, for a 100-year life cycle. SFH cause greater impacts than apartments in multifamily buildings, as they have larger floor area, but on a per m^2 and per capita basis, metrics are comparable. According to this study, there were 16,233,830 people living in 4,960,716 SFH in 2010 in Spain (and 30 M more living in 11 M apartments), or 3.27 occupants per SFH (2.56 per apartment). Of the 15 Midpoint impact categories identified, the study expresses 10 with metrics that need conversion to be compared with the methods used in our article. (Dong et al., 2021) has developed conversion factors to solve this problem. But still, three Midpoint impact categories relevant for our article, and all Endpoint, are missing at (Lavagna et al., 2018). In order to find comparable studies, (Dong et al., 2021) conversion factors have been applied where possible at (Lavagna et al., 2018) results, giving per m^2 a 50-year life cycle adjusted GWP of 1078 kg $CO_2eq{\cdot}m^{-2}$, Fine particulate matter of 0.51 kg PM2.5 eq, Water resource depletion of 9.69 m^3, and Land use of 1415 m^2y^{-1} crop·eq.

Other attempts have been made to benchmark impacts of residential buildings per m^2, as in the case of typical Spanish multifamily buildings, with an average of 73.10 m^2 NFA apartments, for a 50-year life cycle, including 19 impact categories assessed with the same Midpoint methodology as in our article, but without Endpoint analysis (Izaola et al., 2023). That study gives per m^2, among other less relevant data, a GWP of 1913.8 kg CO_2eq, Fine particulate matter of 3.6 kg PM2.5 eq, Water consumption of 64.7 m^3, Land use of 35.8 m^2y^{-1} crop·eq, Human carcinogenic toxicity of 230.5 kg 1,4-DCB, and Freshwater ecotoxicity of 179.6 kg 1,4-DCB. That study separates GWP in Operational and Embodied carbon to highlight energy and material issues. Building techniques and materials' choice also influence LCA results of buildings. Four examples from Slovakia (Moňoková and Vilčeková, 2020) show that the best results come from their Straw house, except in the Renewable Energy and Water Footprint impact categories. Some comparable metrics include a GWP of 1700 kg CO_2eq for the brick house, 330 for the Straw SFH, 1400 for the earth house, and 970 kg CO_2eq for the timber one. Eight other impact categories are compared in the four scenarios. Similar results can be found at (Muñoz et al., 2023), where straw and adobe buildings reduce respectively 40, 30 and 20 % the HH, resource depletion and ED average impacts of a conventional concrete and brick house.

At material level, comparative studies between cement and lime as mortar base indicate that the latter performs better in terms of biodiversity. Lime, being more flexible and porous, has better hygroscopic control, which attracts insects and rodents, which in turn attract birds, improving the surrounding ecosystem. As it has lower emissions than cement, it also lowers GWP (Mukherjee and Roy, 2020). Another study comparing steel structures with diversely managed timber gives a 1000:1 ED ratio of steel versus selectively logged native forest timber, with intermediate ratios of 100:1 versus international plantation timber and 500:1 versus clear fell native forest timber (Nolan et al., 2009). When comparing wood- and concrete-based frame buildings, LCA gives a carbon footprint of 219 kg $CO_2eq{\cdot}m^{-2}$ for concrete and 87 kg $CO_2eq{\cdot}m^{-2}$ for wood (40 % that of concrete). The concrete building consumed 850 l of fresh water per m^2, the wooden one 230 l/m^{-2} (27 %); and 1519 $MJ{\cdot}m^{-2}$ of energy, compared to 510 (33 %). It also consumed a ton of non-renewable material per m^2, compared to 327 $kg{\cdot}m^{-2}$ for wood (32 %). Social LCA data are also relevant as the concrete building causes 855 occupational accidents for every million m^2 and the wooden one 11 (1 %) (Linkevičius et al., 2023). Another Cradle-to-Gate analysis (Arduin et al., 2022) of five earth-based techniques comparing the Embodied Carbon and Embodied Energy per kg of 2-storey bearing walls made of these techniques, found the best results in the Cob technique, except the Embodied energy of compressed earth blocks, which was 77 % that of Cob. More environmental details on Compressed earth block and Rammed earth techniques are presented in another study from (Fernandes et al., 2019), with 9 impact categories. On average, Rammed earth has −7.5 % impact.

The circular economy model has entered the urban, building and material realms aiming at enlarging the life cycle of products and reducing waste. The decarbonization potential of this model has been assessed (Nußholz et al., 2023). Slowing resource solutions could bring up to 99 % savings in GHG emissions per functional unit, and closing resource solutions by 30–50 %, although a case-by-case quantification is crucial (Gallego-Schmid et al., 2020). At a city level, participatory approaches and decision making science are largely missing but necessary (Rios et al., 2022). However, when local materials, techniques and agents are included in the circular economy case, the model can mitigate pressures on biodiversity. It so happens in a Finnish case on quarrying, forest management and the Real Estate sector identifying seven critical factors, of which cascading the reuse of wood materials shows the highest potential (Ruokamo et al., 2023). Retrofitting is the clearest circular economy approach for buildings. It has been assessed that through an optimal retrofitting plan, 39 % life-time cost-saving, 55 % life-time energy reduction and 59 % life-time carbon reduction can be achieved at an investment cost of £1.32×10^6 (Luo and Oyedele, 2021). Moreover, retrofitting makes the energy required for building conditioning affordable for 84 % of households (Ma'bdeh et al., 2023). However, in Spain the ratio of building refurbishment is only 0.8 % of residential buildings per year (Marmolejo-Duarte et al., 2022).

According to official Spanish data, average yearly operational energy consumption of SFH is 15,514 kWh (14,991 in the Atlantic, 19,654 in central Spain and 13,246 in the Mediterranean) and that of apartments, 7547 (IDAE, 2022). Of the 19,654 kWh for central Spain, and in particular for climate zone D3, 75 % (14,838 kWh) comes from the combustion of fuels to provide HVAC+Hot Water, 6 % (1136 kWh) from electrical HVAC+Hot Water, 3 % (557 kWh) from lighting, and the remaining 16 % (3003 kWh) from electrical appliances. Official statistics give an average SFH floor area of 144 m^2 (INE, 2011), recently updated to 152 m^2 (INE, 2023). With these figures, the average energy-related emissions of a Spanish SFH in the period 2011–2020 were 26.92 kg CO_2 $eq{\cdot}m^{-2}y^{-1}$. Moreover, the 2020 Carbon Cartography Report, following Scope 3 Carbon Footprint, gives an average 5.5 t CO_2 $eq{\cdot}y^{-1}$ per capita in Spain (Clean Planet, 2021). This footprint is distributed in Lifestyle (14 %), Food (34 %), Transport (42 %) and Home (10 %). These results are lower than the European Carbon Footprint Map (Ivanova et al., 2017), giving EU and Spanish averages of 11 t CO_2 $eq{\cdot}y^{-1}$ per capita, with a distribution in products and Services (42 %), Food (21 %), Mobility (25 %) and Shelter (11 %). Income strongly influences results, which in Spain means inequalities such as the richest 5 % being responsible for 33 % of the domestic carbon footprint, while the poorest 45 %, of the 23 % (López et al., 2020). Another Spanish projection from 2018 to 2030 on the effects of decarbonization policies to meet thermal demands leads to reductions in the HH (64.5 %), GWP (62.0 %) and Resource Consumption (59.5 %) categories. However, ED increases 16.5 %. Damages due to the 2030 electricity generation scenario on HH, GWP and Resource Consumption decrease by 45 %, 43 % and 39 %, respectively; but on ED increase 70 % (González-Prieto et al., 2020).

The above state of the art was searched in Sciencedirect, Nature and Google Scholar, using the keywords "building" OR "single-family house" AND "biodiversity" AND "ecotoxicity", filtering articles from 2013 on, and with >50 citations. Initially, 39 were obtained. The search was extended to articles from 2001 onwards, regardless of their citations, finding 147, of which 18 were repeated. 129 articles were grouped into the following impact levels: General (14), Ecosystem (21), Urban (27), Building (34) and Material (17). Of these, 22 are reviews or systematic reviews; 13 at impact, 6 at Urban and 3 at Building level, and were discarded. A final quality and timely filter discarded articles older than ten years and with less than ten citations, finding 61 articles grouped as General (10), Ecosystem (8), Urban (11), Building (18) and Material (8). A final group of 6 articles contextualizing the situation in Spain was added. This article tries to fill the research gap on biodiversity impacts of buildings in Spain.

3. Methods, data and tools

The methodology used for this research is Life-cycle Assessment (LCA) using the ReCiPe 2016 LCIA Hierarchical (H) method at Midpoint and Endpoint, where midpoints help to understand the cause-impact pathway and endpoints reflect damage to HH, ED and resource scarcity. The two approaches are complementary in that Midpoint has a stronger relation to environmental flows and a relatively low uncertainty, while Endpoint provides better information on the relevance of the environmental flows, but is also more uncertain (Huijbregts et al., 2017). OpenLCA software with data from Ecoinvent 3.9 has been used for their acceptance in the scientific community, their wide inclusion of impact categories, the clarity along the cause-effect pathways, and the specific biodiversity metrics, including ecosystems, land use and an eight-group species taxonomy. In a review of the applicability of 64 methods in biodiversity impact assessment, ReCiPe is also recommended (Damiani et al., 2023). However, it only includes biodiversity community composition and not ecosystem functions or structure, which, on the other hand is only provided by the too specific "Habitat Change Potential" method.

Model parameters include choosing the cut-off criteria of allocation of environmental burdens of materials, applying EU regionalization wherever possible, and defining as scope the whole building construction, use and end-of-life processes in terms of NFA; reduced to m^2 as functional unit. The system boundary is a cradle-to-grave LCA from stage A to stage C. EN15978 modules B4 (Replacement) and B5 (Refurbishment) have not been considered in the 50-year life-cycle period due to lack of data and in accordance with a building culture which does not favour any of both (Val, 2011). For the inventory of the scenarios, in average, 33 input flows and 16 output flows have been introduced at the OpenLCA model of the four buildings (see Tables S3 to S6 of the Supporting information file). An estimation of 98 % of the average 160 measured items from the original bill of materials of the studied buildings were grouped in average 44 streams and included with few adjustments as inputs. 18 impact categories at Midpoint, with Global Warming Potential (GWP) separated in embodied and operational carbon, and 22 at Endpoint, with aggregated metrics per species.yr, DALY and USD2013, are presented.

Four specific metrics highlight the purpose of this article: the two Midpoint metrics are kg CO_2eq, as it provides context to buildings' LCA, and kg 1,4-DCB (dichlorobenzene), a chemical compound commonly used as a solvent, deodorizer, and insect repellent. Because of its characteristics and wide use in toxicity testing, it is often chosen in LCA as an ecotoxicity reference substance. Dichlorobenzene appears in the building industry for wood preservation, as a concrete formwork release agent and in adhesives, sealants, paints and coatings. The two endpoint metrics are species extinction per year "species.yr" and Disability-Adjusted Life Years "DALY". Species extinction quantifies the potential impact of activities on species' richness over a specified period. It considers both the number of species locally extinct and the duration of the impact. DALY is a measure of overall disease burden considering the years of life lost due to premature death for humans, plus the years of healthy life lived with a disability (Huijbregts et al., 2017). Both metrics allow for a quantitative comparison of processes or products in terms of their biodiversity impact.

Full LCA at Mid- and End-point of the four scenarios have been calculated, using a conventional brick house as base scenario, on which to compare three low-impact scenarios. Brick masonry is the standard building system in Spain, with 98 % of SFH. The optimized scenarios are less common, but current 1 % timber buildings are growing, and earth-based buildings remain present in older buildings all over the country, except on the north coast (Arriaga, 2020). While the newest national statistic (INE, 2023) reports 152 m^2 as average area of SFH, 27.5 % of the SFH have an average surface above 180 m^2, which is the largest statistical category by area. A real case with this size has been considered representative for central Spain. Also, plot area definition is determined by local urban codes, with a wide spectrum between 160 m^2 for row houses and 2500 m^2 for detached homes. However, in the region of the chosen case, average plot area is 804 m^2 (Santos Preciado and García Lázaro, 2012), which fits to the 800 m^2 of the case representing the base scenario.

For all 18 Mid- and 22 End-point impacts, comparisons are made per m^2. GWP Midpoint impact is divided into Operational Carbon (OC) and Embodied Carbon (EC). OC has been calculated from the energy certification. The five Midpoint impacts related to ecotoxicity are aggregated under the same metric (kg 1,4-DCB) and their relative weights considered to find the most influential one. The processes that contribute most to each indicator are then presented. This allows to draw conclusions to diminish biodiversity impacts. A similar approach is applied to the two mentioned Endpoint metrics. 12 impacts sharing the "species.yr" metric and the DALY metric are aggregated, their relative weights compared to find the most influential, and finally the most relevant contributing processes are explained. A study on recommendations for communicating aggregated buildings LCA results includes this proposal and encourages practitioners to transparently experience on this to help convey LCA messages (Gomes et al., 2022). Table S1 of the Supporting information file presents the categories that are aggregated at each impact method.

3.1. Description of scenarios

Four scenarios have been created to measure the impact of conventional 98 % of Spanish SFH, (Arriaga, 2020) and three low-impact SFH to reach virtually all Spanish SFH. All scenarios fall within the same climate zone (D3 according to Spanish building regulation) to facilitate energy usage comparison. For all four scenarios, the functional unit is a square meter of the built area of the SFH, the system boundary is a cradle-to-grave LCA from stage A to stage C according to EN15978, excluding replacement and refurbishment, in a 50-year life cycle after which the building is demolished and sent to landfill.

3.1.1. Scenario 0 (SC0: Brick ± Concrete)

The Base Scenario represents 98 % of Spanish SFH (Arriaga, 2020). It is a detached (three members) home in the south of Madrid (Getafe, 630 m above sea level (a.s.l.)), built in 2016 on a previously urbanised flat 800 m^2 plot surrounded by planted pine trees. It has a Net Floor Area (NFA) of 151 m^2 (main floor 120 m^2, mezzanine 31 m^2; total built 181 m^2). An envelope surface of 768.6 m^2 confines a volume of 488.7 m^3, giving a shape factor of 1.57 (Shape factor (SF) = envelope surface/volume). Foundations and structure are made of reinforced concrete, and facades of cavity brick walls insulated with 5 cm of mineral wool and finished inside and outside with cement mortar and painting. The gable roof slab (also insulated with 5 cm of mineral wool) and the floor slab are bidirectional reinforced concrete sheds with an axes distance of

82 cm. Roofing is finished with ceramic tile. Inside floorings are laid with ceramic tile on the wet rooms and hard wood on the rest. It weights 443 t, of which foundations and structure 403 t and ceramics 27 t. Windows are thermal brake aluminium framed with double glazing. It has an energy certification Class B (15.12 kg $CO_2eq{\cdot}m^{-2}y^{-1}$ emissions and 66.72 $kWh{\cdot}m^{-2}y^{-1}$·non-renewable energy demand). Heating is provided by a Natural gas 4 kW heater. Lay-out and main elevation can be found in the Supporting information file, as Figs. S1 and S2.

3.1.2. Scenario 1 (SC1: Timber ± Passivhaus)

Semi-detached (four members) SFH in the outskirts of Madrid (770 m a.s.l.), built in 2020 on a semi-arid flat 250 m^2 sprawl-type plot with 2 pine trees, one palm and one fig tree, with NFA 157 m^2 (built 216 m^2). The other adjacent semi-detached SFH is structurally and thermally isolated by a party wall. An envelope surface of 441.2 m^2 confines a volume of 691 m^3, giving a SF of 0.64. It is built under standard Passivhaus (Moreno-Rangel, 2020) with an energy certification Class A (7.42 kg $CO_2eq{\cdot}m^{-2}y^{-1}$ emissions and 40.82 $kWh{\cdot}m^{-2}y^{-1}$·non-renewable energy demand). It has no underground floor and the outer structure, inner partitions, floors and roof are made of Cross Laminated Timber (CLT) (balloon frame technique). Foundations are superficial (0.8 m below ground) strip footing concrete blocks suitable for a light building. It has an 8.7*9.5 (82.6 m^2) lay-out on two full floors plus half floor under an N-S gable roof. It weights 84 tons, of which foundations 40 t and timber 35 t. It has a heat-recovery ventilation system solved with an 8 kW heat pump. Peak electricity demand is 9.9 kW, supported by a 2.6 peak kW PV installation on the south facing slope of the roof. Envelope insulation is made of 40 cm wood fibre except ground floor 10 cm cork. Windows are wood-framed with double low-emissive glazing. This house has automated devices for sun shading, HVAC, PV, artificial lighting, door opening, fire safety, air ventilation and air quality systems. Painting and surface finishes are VOC-free ecological products. Lay-out and main elevation can be found in the Supporting information file, as Figs. S3 and S4.

3.1.3. Scenario 2 (SC2: Straw ± Renewables)

Detached (four members) SFH in the north mountains of Madrid (Robledo de Chavela, 900 m a.s.l.), built in 2019 on a south-facing 15 % slope mixed with granite rock outcrops and local wild shrubs: rockrose, heather, broom, rosemary, thyme and medium size broom, rosemary, thyme and holm oak. The plot has 10,215 m^2, is not fenced and the nearest home is 260 m down the gravel road. It is built with a very light hybrid timber-and-straw-bale modular bearing wall system. Three 7*6 m modules with a total NFA of 90 m^2 (built 123 m^2) are laid on one floor over a levelling cyclopean concrete slab filled with the local granite rock. It weights 69 t, of which the concrete slab 51 t and the straw-bales, 1.1 t. An envelope surface of 386.8 m^2 confines a volume of 362.9 m^3, giving a SF of 1.07. It has an energy certification B (12.59 kg $CO_2eq{\cdot}m^{-2}y^{-1}$ emissions and 65.09 $kWh{\cdot}m^{-2}y^{-1}$·non-renewable energy demand). The lower part of the single south facing roof slope made of I-Joist and OSB boards insulated with straw, is covered with greenroof (5 cm substrate) while the upper part hosts 4 m^2 of solar thermal panels (300 l tank) and 6.65 m^2 of photovoltaic panels (1.3 peak kW). In the living room there is a 7 kW logwood fireplace with stove. Windows are wood-framed with double glazing. Waste water is bio-depurated on-site. Lay-out and main elevation can be found in the Supporting information file, as Figs. S5 and S6.

3.1.4. Scenario 3 (SC3: Earth ± Bioclimatic)

Detached (six members) two floor SFH in Catalonia, Lleida (Balager, 266 m a.s.l.), built in 2019 on a flat urban plot of an agricultural village at the crossing of two rivers. The two adults work at home. The site contains radon gas and a filtering membrane is laid between the foundation and the ground floor to avoid it entering the house. It has a NFA of 224 m^2 (total built 276 m^2). An envelope surface of 560.1 m^2 confines a volume of 828 m^3, giving a SF of 0.68. It is built with structural walls of rammed earth extracted from the site. The foundation is made with cyclopean bastard concrete from the site boulders and pebbles, found below 1 m of sand and clay. It weights 580 t, of which 157 t to rammed earth. The strip footing below the bearing walls are the same type, but reinforced with corrugated steel. The floors and roof structure are made of local pine tree timber (Pyrenees, 150 km) with 2/3 of flat greenroof finish and 1/3 of wooden pinned slates. The roof insulation is 20 cm of cotton while North and East external walls' cotton insulation is 14 cm thick, and at South and West, 7 cm. It is a bioclimatic Energy+ building (Kumar and Cao, 2021) under a non-ventilated rammed earth thermal wall behind a greenhouse, with energy certification A (2.4 kg $CO_2eq{\cdot}m^{-2}y^{-1}$ emissions and 14.1 $kWh{\cdot}m^{-2}y^{-1}$·non-renewable energy demand). In the upper floor, sleeping rooms partition walls are 5 cm earth mortar radiant walls on the timber structure, operated with a 1.2 kW heat pump with a 200 l tank. These rooms also have a skylight going through the greenroof. Windows are wood-framed with triple low-emissive glazing. For occasional heating there is an extra pellet 17 kW furnace. It also has a 4.5 kW peak PV installation producing more energy than demanded. Lay-out and main elevation can be found in the Supporting information file, as Figs. S7 and S8. Table 1 presents a general comparison of building metrics of the four scenarios.

4. Results

Table 2 summarizes the four biodiversity impact categories studied at the four scenarios, and estimates the overall impacts of the Spanish 4,960,716 (Lavagna et al., 2018) SFH stock represented by our base scenario. Spanish SFH emit 1.16 Gt CO_2eq to the atmosphere in a 50-year life cycle, of which 39.9 % is embodied in the building materials. They also pollute land, water and human health with 10.2 Gt 1,4-DCB. They drive 6052 species extinct, and lose 3.03 M years of human life. Divided by the 16 M people living in the Spanish SFH stock, each inhabitant lost 0.19 DALY; or 68.1 days of their lives. The Earth house gives the best results, in average 63 % below the Brick SFH. Its energy+ solution effectively cuts GWP to 19 % that of SC0. The initial graphical abstract illustrates these data.

Table 3 details all the impact categories of the scenarios at Mid- and Endpoint, per m^2. At Midpoint, GWP is decomposed in Operational and Embodied Carbon, and Ecotoxicity metrics are aggregated and appear underlined for clarification. At Endpoint, "species.yr", "DALY" and "USD2013" metrics are also aggregated. Red cells highlight the worst results, and green ones, the best.

Taking Scenario 0 as base for comparison (100 % green line), the following logarithmic scales present the relative impacts at Mid- and Endpoint methods of the previous Table 3 results (metrics per m2). Fig. 1 shows the Midpoint impacts comparison, while Fig. 2, the Endpoint's. Land use impacts are worse than SC0 in scenarios 1–3 and Marine eutrophication impact of the Earth house exceeds averages (701 % at Midpoint and 700 % at Endpoint). Average impact of the Timber house is 71 % at Midpoint, and 66 % at Endpoint of the Brick home. The Straw SFH averages are 67 % and 61 % respectively, and the Earth house's, 87 % and 76 %. The Earth house has the lowest results in 26 of the 40 indicators and 12 highest results. The Timber home, 8 lowest and 5 highest. The Straw SFH has 6 lowest and 23 highest results.

Table 4 presents the contribution of the main LCA processes on GWP. The Operational Carbon has an average weight of 64.4 %, except in the Earth house, which, as mentioned, is an Energy+ house. Where there is a photovoltaic installation, it ranks second. Cement presents strong differences in the four scenarios, and their specific processes are commented at the discussion section. The only characteristic material of any scenario that appears as high contributor is CLT in the Timber house.

Table 5 presents the contribution of the main LCA processes on Terrestrial ecotoxicity, at Midpoint. Terrestrial ecotoxicity carries 76 % of the 5 ecotoxicity indicators, as seen in Table S2 of the Supporting information file. Copper-containing items rank high on this indicator. Electric wiring appears as the main toxic building component with an

Table 1
Comparison of building metrics of the four scenarios.

	Unit	SC0 Brick	SC1 Timber	SC2 Straw	SC3 Earth
Total weight	kg	433,353	84,008	68,817	580,931
Built surface	m^2	181	216	123	276
Weight/m^2	kg/m^2	2394.2	388.9	559.5	2104.8
Envelope surface	m^2	768.6	441.2	386.8	560.1
Confined volume	m^3	488.7	691	362.9	828
Shape factor	m^{-1}	1.57	0.64	1.07	0.68
Non-renewable energy demand	$kWh \cdot m^{-2} y^{-1}$	66.72	40.82	65.09	14.1

Table 2
Summary of biodiversity impacts of the scenarios per m^2, and the Spanish SFH stock on absolute values.

	Unit	SC0 Brick	SC1 Timber	SC2 Straw	SC3 Earth	SFH stock
Impact category						
Global Warming Potential (GWP)	kg CO_2 eq/m^2	1292	685	757	247	1,160,857 M
Of which Embodied Carbon (EC)	kg CO_2 eq/m^2	516	216	215	287	463,718 M
5 aggregated ecotoxicity metrics	kg 1,4-DCB/m^2	11,399	8218	9215	6199	10,235,357 M
12 aggregated species.yr metrics (ED)	species.yr/m^2	7.54E-06	5.21E-06	5.08E-06	3.12E-06	6052
8 aggregated DALY metrics (HH)	DALY/m^2	3.37E-03	1.88E-03	2.05E-03	1.11E-03	3,029,387
Compared to base scenario (brick)						
Global Warming Potential (GWP)	% kg CO_2 eq/m^2	100 %	53.0 %	58.6 %	19.1 %	
5 aggregated ecotoxicity metrics	% kg 1,4-DCB/m^2	100 %	72.1 %	80.8 %	54.4 %	
12 aggregated species.yr metrics (ED)	% species.yr/m^2	100 %	69.1 %	67.4 %	41.4 %	
8 aggregated DALY metrics (HH)	% DALY/m^2	100 %	55.8 %	60.8 %	32.9 %	

average contribution of 49 %. Four processes (from average 55), are enough to account for an average weight of 86 % of the indicator.

Table 6 presents the contribution of the main LCA processes on Land use, at Endpoint. Land use carries 39 % of the 12 ED indicators except in SC0, as seen in Table S2 of the Supporting information file. Each building has a different behavior in this realm, and it is strongly tied to its main structural system. The characteristic material of the Timber house clearly bears with most of its impacts. In the case of the Straw home, the straw-bales are framed within glued timber bearings, as also happens with the floors of the Brick SFH. Also in the Earth house, structural timber is present at the greenhouse, roof structure and cladding, with high contribution. The cotton insulation here appears as another crop, next to forestry and cereal straw, showing their impact on land use.

Table 7 presents the contribution of the main LCA processes on fine particulate matter formation, at Endpoint. This indicator carries 35 % of the 8 HH indicators, as seen in Table S2 of the Supporting information file. The Operational energy contributes an average 49 %, except in the energy + Earth house. Electric wiring ranks second in all scenarios, and where there is a photovoltaic installation, third. Also, the ceramic tile production appears high in all houses. Diverse processes related to the structural system of each scenario appear, as CLT in SC1 and cotton in SC3.

Due to the outstanding impact of the Marine eutrophication Endpoint indicator on the Earth house seen at Fig. 2, the related contribution tree was also calculated to find out that 61 % of the weight comes from the wastewater treatment, and 32 % comes from the market for fibre cotton process. The uncertainty of this process, and other limitations of this study are discussed below.

5. Discussion

This article provides new biodiversity-related data on the impacts of housing in Spain. It updates Midpoint and Endpoint impact categories by applying the ReCiPe 2016 (H) method in a 50-year life cycle full LCA, with exception of replaceable components or building refurbishment. A longer timespan might have allowed the inclusion of these two modules, but still data was missing and complying with international standards of 50 years lifecycle was considered a priority. Comparing results with other reviewed studies was difficult due to different metrics and LCA approaches. But it has been possible to compare 15 Midpoint impact categories between a Spanish average apartment (Izaola et al., 2023) mentioned in the literature review and the conventional SFH of our article. Table 8 presents indicators per built m^2 and their variation. On average, the SFH impacts are 77 % that of the apartment, except four categories that present higher impacts, Stratospheric ozone depletion (114.4 %), Freshwater ecotoxicity (251.3 %), Human non-carcinogenic toxicity (103 %) and Land use (125.4 %). If we are right and a built square meter of SFH impacts half of the Fossil resource scarcity (50.2 %), Fine particulate matter formation (49.5 %), Mineral resource scarcity (54.2 %) or Terrestrial acidification (45.8 %) than that of an apartment in a multifamily building, widely accepted urban policies that defend the idea of a dense, compact city versus scattered SFH are at least challenged. A similar conclusion was reached at a study (Muñiz et al., 2012) using the ecological footprint methodology, including mobility. Concerning Land use and Freshwater ecotoxicity, it is consistent among all scenarios of this paper that use of timber pays its toll at these impact categories. Extracting minerals from quarries (for bricks or concrete) spoils less land and water, in accordance with findings from (Ruokamo et al., 2023). What is efficient for logistics and economy of scale, may not be optimal for biodiversity protection but also exploitation of timber has a scale limit just as not any reforestation sequesters carbon. Some golden rules must be followed to mitigate global warming, recover biodiversity and enhance habitats for all (Di Sacco et al., 2021). Single-family homes studied here suggest better human and ecosystem health than multi-family flats, especially scenarios 1 to 3. The discussion is nevertheless open. However, the standard SFH considered as scenario 0 does not include an underground garage, which is common in the Spanish SFH, as well as in the multifamily building stock. To make the four researched scenarios more comparable, the chosen SC0 also lacked basement, although, when there is one, in average it yields 15 % of the results (Hartmann et al., 2022).

A comparison on scenarios is also possible thanks to (Moňoková and Vilčeková, 2020). The Timber and Brick buildings in this research reduce impacts of the three comparable categories as can be seen in Table S7 of the Supporting information file. However, the Straw and Earth buildings present too large variations due to different approaches to the technique and main material. Comparability is difficult due to differing research conditions.

Table 3
Impact categories of the studied houses at Mid- and End-point per m^2. Best in green, worst in red.

Midpoint Impact category	Unit	SC0 Brick	SC1 Timber	SC2 Straw	SC3 Earth
Fine particulate matter formation	kg PM2.5 eq/m²	1.78	1.13	1.21	0.59
Water consumption	m^3/m²	57.52	23.16	6.24	23.60
Stratospheric ozone depletion	kg CFC11 eq/m²	3.81E-04	3.25E-04	2.91E-04	2.14E-04
Terrestrial ecotoxicity	kg 1,4-DCB/m²	8,351.44	6,497.92	7,325.83	4,566.63
Human non-carcinogenic toxicity	kg 1,4-DCB/m²	1,898.69	1,391.30	1,493.65	1,175.54
Fossil resource scarcity	kg oil eq/m²	446.33	204.81	225.28	49.89
Terrestrial acidification	kg SO_2 eq/m²	3.99	2.56	2.77	1.24
Ozone formation, Terrestrial ecosystems	kg NO_x eq/m²	3.16	1.74	1.78	1.12
Land use	m^{2}a crop eq/m²	134.72	249.52	192.74	159.93
Marine ecotoxicity	kg 1,4-DCB/m²	549.78	155.16	182.10	219.93
Marine eutrophication	kg N eq/m²	0.04	0.06	0.04	0.25
Mineral resource scarcity	kg Cu eq/m²	8.45	5.05	6.15	10.00
Human carcinogenic toxicity	kg 1,4-DCB/m²	148.11	50.26	68.50	58.05
Ozone formation, Human health	kg NOx eq/m²	2.99	1.65	1.68	0.98
Freshwater eutrophication	kg P eq/m²	0.33	0.21	0.23	0.14
Freshwater ecotoxicity	kg 1,4-DCB/m²	451.33	123.16	145.01	178.92
Ionizing radiation	kBq Co-60 eq/m²	18.80	18.71	18.71	16.76
Global warming potential (GWP)	kg CO_2 eq/m²	1,292.87	684.58	756.54	246.99
- Operational carbon	kg CO_2 eq/m²	776.42	469.06	541.11	-40.15
- Embodied carbon	kg CO_2 eq/m²	516.45	215.52	215.43	287.14
total	kg 1,4-DCB/m²	11,399.35	8,217.80	9,215.09	6,199.08

Endpoint Impact category	Unit	SC0 Brick	SC1 Timber	SC2 Straw	SC3 Earth
Ionizing radiation	DALY/m²	1.59E-07	1.74E-07	1.59E-07	1.42E-07
Terrestrial ecotoxicity	species.yr/m²	9.54E-08	7.42E-08	8.36E-08	5.21E-08
Fossil resource scarcity	USD2013/m²	1.46E+02	6.58E+01	7.25E+01	1.41E+01
Global warming, Terrestrial ecosystems	species.yr/m²	3.65E-06	1.90E-06	2.11E-06	6.88E-07
Human carcinogenic toxicity	DALY/m²	4.92E-04	1.67E-04	2.27E-04	1.93E-04
Land use	species.yr/m²	1.20E-06	1.90E-06	1.71E-06	1.41E-06
Ozone formation, Terrestrial ecosystems	species.yr/m²	4.07E-07	2.25E-07	2.30E-07	1.45E-07
Freshwater ecotoxicity	species.yr/m²	3.12E-07	8.52E-08	1.00E-07	1.24E-07
Water consumption, Terrestrial ecosystem	species.yr/m²	7.73E-07	3.13E-07	8.43E-08	3.19E-07
Water consumption, Aquatic ecosystems	species.yr/m²	3.47E-11	1.40E-11	3.77E-12	1.43E-11
Stratospheric ozone depletion	DALY/m²	2.02E-07	1.73E-07	1.54E-07	1.14E-07
Human non-carcinogenic toxicity	DALY/m²	4.33E-04	3.17E-04	3.41E-04	2.68E-04
Mineral resource scarcity	USD2013/m²	1.96E+00	1.17E+00	1.42E+00	2.31E+00
Terrestrial acidification	species.yr/m²	8.29E-07	5.56E-07	5.88E-07	2.62E-07
Marine eutrophication	species.yr/m²	6.16E-11	1.07E-10	5.83E-11	4.32E-10
Global warming, Freshwater ecosystems	species.yr/m²	9.89E-11	5.24E-11	5.79E-11	1.89E-11
Water consumption, Human health	DALY/m²	1.28E-04	5.14E-05	1.38E-05	5.24E-05
Freshwater eutrophication	species.yr/m²	2.20E-07	1.43E-07	1.55E-07	9.29E-08
Marine ecotoxicity	species.yr/m²	5.78E-08	1.63E-08	1.91E-08	2.31E-08
Fine particulate matter formation	DALY/m²	1.12E-03	7.10E-04	7.61E-04	3.69E-04
Ozone formation, Human health	DALY/m²	2.71E-06	1.48E-06	1.54E-06	9.06E-07
Global warming, Human health	DALY/m²	1.20E-03	6.35E-04	7.02E-04	2.29E-04
total	species.yr/m²	7.54E-06	5.21E-06	5.08E-06	3.121.14E-06
total	DALY/m²	3.37E-03	1.88E-03	2.05E-0.3	1.11E-03
total	USD2013/m²	148.33	66.93	73.90	16.38

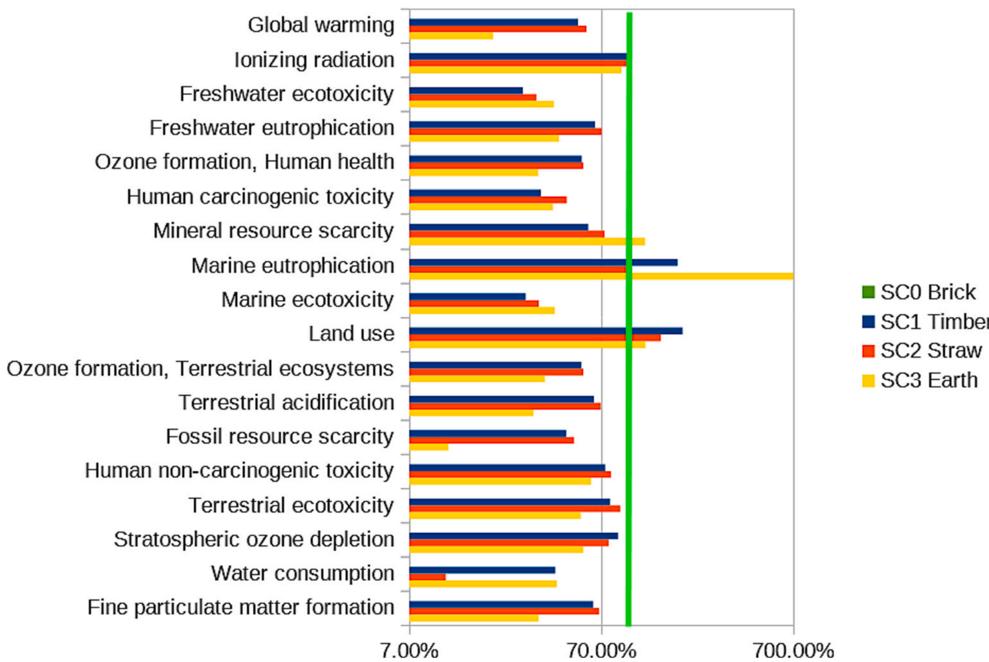

Fig. 1. Midpoint impact category comparison (Brick house 100 %, as green line).

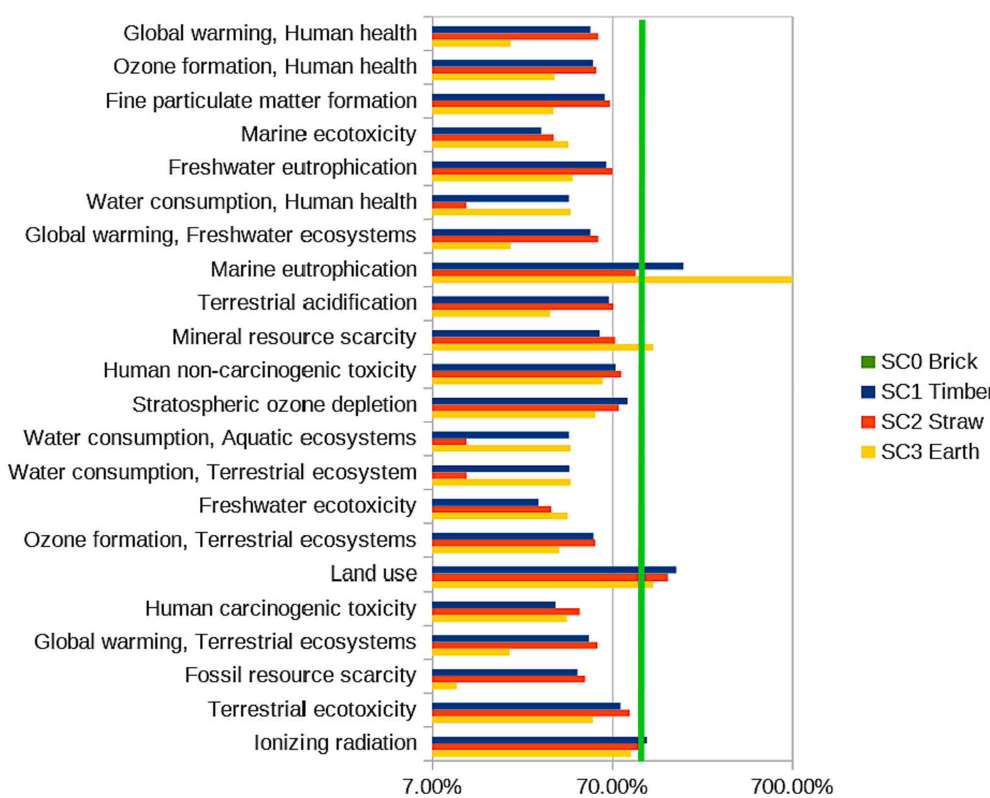

Fig. 2. Endpoint impact category comparison (Brick house 100 %, as green line).

One limitation of this article is that ReCiPe (and other methods such as Impact2002+) do not take social preferences into account when calculating DALY. In contrast, Eco-indicator 99 and other methods do consider them, although they are culturally influenced. Also, the DALY compound of "years lived with disability" has very different implications in Europe or other parts of the world. Further research could integrate Social LCA with HH impacts such as DALY. This reinforces the idea that biodiversity studies should enter and reframe environmental impacts of buildings. This is aligned with (Frischknecht et al., 2016) in suggesting to explore the sensitivity of LCA results to metrics other than GWP. GWP can act as spearhead for other indicators. This article has aggregated common metrics (5 ecotoxicity-related at Midpoint, and 12 species.yr-related and 8 DALY-related, at Endpoint) that present different weights. It can be seen that Terrestrial ecotoxicity (average 76 %), Land

Table 4
Main contributing LCA flows on Global Warming Potential (GWP).

Global warming potential, % contribution kg CO2 eq	SC0 Brick	SC1 Timber	SC2 Straw	SC3 Earth
Market for electricity, low voltage | electricity, low voltage | Cutoff, U - BD	60.05 %	68.52 %	71.31 %	
Market for PV slanted-roof installation, 3kWp, multi-Si panel | Cutoff, U - GLO		4.04 %	3.21 %	15.04 %
Market for cross-laminated timber | cross-laminated timber (CLT) | Cutoff, U - RER		3.23 %		
Cement production, Portland | cement, Portland | Cutoff, U - IN	13.78 %	3.22 %	3.40 %	26.65 %
Window frame production, wood, U = 1.5 W/m2K | Cutoff, U - RER		2.96 %	1.99 %	4.09 %
Alkyd paint production, solvent-based, in 60 % solution state | Cutoff, U - RoW			2.20 %	4.59 %
Structural timber production | structural timber | Cutoff, U - RER				3.28 %
Market for fibre, cotton | fibre, cotton | Cutoff, U - GLO				3.64 %
Treatment of waste rubber, municipal incineration | Cutoff, U - EU without CH				5.66 %
Market for seal, natural rubber based | seal, natural rubber based | Cutoff, U - GLO				3.88 %
Reinforcing steel production | reinforcing steel | Cutoff, U - AT	2.69 %			4.41 %
Market for furnace, pellet, 15 kW | furnace, pellet, 15 kW | Cutoff, U - GLO				6.04 %
Glazing production, triple, U < 0.5 W/m2K | Cutoff, U - RER		1.18 %	0.96 %	3.19 %
Market for natural gas, low pressure | natural gas, low pressure | Cutoff, U - MX	5.49 %			
Total	82.01 %	83.15 %	83.07 %	80.47 %

Table 5
Main contributing LCA flows on Terrestrial ecotoxicity.

Terrestrial ecotoxicity, % contribution kg 1,4-DCB	SC0 Brick	SC1 Timber	SC2 Straw	SC3 Earth
Market for cable, three-conductor cable | cable, three-conductor cable | Cutoff, U - GLO	43.21 %	51.16 %	48.19 %	52.77 %
Market for electricity, low voltage | electricity, low voltage | Cutoff, U - BD	27.31 %	21.21 %	21.63 %	
Market for photovoltaic slanted-roof installation, 3kWp, multi-Si panel | Cutoff, U - GLO		14.99 %	11.67 %	28.87 %
Market for solar collector system, Cu flat plate collector, one-family house, hot water | solar collector system | Cutoff, U - GLO	13.12 %		9.08 %	
Total	83.64 %	87.36 %	90.57 %	81.64 %

Table 6
Main contributing LCA flows on Land use.

Land use,% contribution species.yr	SC0 Brick	SC1 Timber	SC2 Straw	SC3 Earth
Market for cross-laminated timber | cross-laminated timber (CLT) | Cutoff, U - RER		48.41 %		
Oriented strand board production | oriented strand board | Cutoff, U - RoW		19.65 %		
Window frame production, wood, U = 1.5 W/m2K | Cutoff, U - RER		9.09 %	8.72 %	7.06
Market for sawnwood, lath, hardwood, dried (u = 10 %), planed | Cutoff, U - RoW		9.07 %		
Glued solid timber production | glued solid timber | Cutoff, U - RER	42.25 %		69.58 %	
Straw production, stand-alone production | straw, stand-alone production | Cutoff, U - RoW			9.91 %	
Structural timber production | structural timber | Cutoff, U - RER				45.80 %
Wood cladding production, softwood | wood cladding, softwood | Cutoff, U - CA-QC				28.89 %
Market for fibre, cotton | fibre, cotton | Cutoff, U - GLO				6.88 %
Cement production, Portland | cement, Portland | Cutoff, U - IN	14.35 %			
Market for electricity, low voltage | electricity, low voltage | Cutoff, U - BD	7.46 %			
Door production, inner, wood | door, inner, wood | Cutoff, U - RoW	7.41 %			
Sand quarry operation, open pit mine | sand | Cutoff, U - BR	4.46 %			
Treatment of waste reinforced concrete, for final disposal | Cutoff, U – EU without CH	3.50 %			
Total	79.43 %	86.22 %	88.21 %	88.63 %

use (average 39 %) and Fine particulate matter (average 35 %) carry the heaviest loads at Ecotoxicity, Species lost and DALY, respectively. In the case of Land use, the importance of forestry (Timber house), cereal crop (Straw house) and cotton crop for the insulation of the Earth house can be seen in scenarios 1–3. The global warming impact on HH at Endpoint has a high average weight (31 %) showing the connection of GWP with biodiversity and health. More details appear in Table S2 of the Supporting information file. All IPBES data mentioned in the introduction of this research are confirmed here. Authors expect these results to support IPBES and IPCC interactions.

Research on the links between LCA and biodiversity at buildings lacks both baselines and Reference Situations (RS), and this article advances on this. Baselines are used in LCA for specific purposes, whereas RS reflect, often at an aggregated level, social preferences related to biodiversity. We agree with (Vrasdonk et al., 2019) that RS for biodiversity in LCA, based on biodiversity targets which are aligned with society's conservation frameworks, could give decision-makers tools to reduce the impacts of buildings. However, we disagree with (Curran et al., 2010) about the value of the shortcomings of these models, and consider that metrics such as those provided here give meaningful Mid- and End-point indicators on biodiversity impacts. We aim to raise awareness, such as the popular image of the orangutan habitat destroyed by the palm oil industry. Average citizens may not know the figures of 0.0035 species.yr lost and 0.0302 DALY (11 days) of 1 ha of palm trees (Obaideen et al., 2019), but if possible, choose food without palm oil. Taking this as an example, we can figure out that an equivalent built surface (1 ha or 55 conventional SFH) impacts with 0.0067 species.yr and 33.756 DALY, almost twice as much ED and more than one thousand times HH damage than palm oil. Will knowing this drive low-impact building decisions?

This research understands that housing is just one of many areas of impact of human activity, with a limited share, even in Europe, representing only 26 % of EU consumption (Sanyé-Mengual et al., 2023), including appliances and household goods; the main share being food (58 %) and not forgetting mobility (16 %). Awareness of biodiversity damage should include all consumption areas, not only those of Europeans, and be done per capita. In fact, we should include hidden energy flows from other world regions (Akizu-Gardoki et al., 2021). Moreover, direct electricity consumption in houses only accounts for 3.6 % of the total national energy footprint, so indirect energy consumption and their

Table 7
Main contributing LCA flows on Fine particulate matter formation.

Fine particulate matter formation, % contribution DALY	SC0 Brick	SC1 Timber	SC2 Straw	SC3 Earth
Market for electricity, low voltage | electricity, low voltage | Cutoff, U - BD	49.21 %	46.81 %	50.26 %	
Market for cable, three-conductor cable | cable, three-conductor cable | Cutoff, U - GLO	8.27 %	12.00 %	11.90 %	16.77 %
Market for photovoltaic slanted-roof installation, 3kWp, multi-Si panel, | Cutoff, U - GLO		5.89 %	4.82 %	15.19 %
Market for cross-laminated timber | cross-laminated timber (CLT) | Cutoff, U - RER		4.85 %		
Ceramic tile production | ceramic tile | Cutoff, U - CH	5.14 %	4.24 %	4.98 %	15.89 %
Window frame production, wood, U = 1.5 W/m2K | Cutoff, U - RER		3.77 %		3.62 %
Oriented strand board production | oriented strand board | Cutoff, U - RoW		3.43 %		
Glued solid timber production | glued solid timber | Cutoff, U - RER			4.22 %	
Market for solar collector system, Cu flat plate, one-family home hot water | Cutoff, U - GLO			3.97 %	
Market for fibre, cotton | fibre, cotton | Cutoff, U - GLO				3.91 %
Cement production, Portland | cement, Portland | Cutoff, U - IN	8.42 %			9.44 %
Structural timber production | structural timber | Cutoff, U - RER				4.57 %
Market for furnace, pellet, 15 kW | furnace, pellet, 15 kW | Cutoff, U - GLO				4.50 %
Alkyd paint production, solved-based in 60 % solution state | Cutoff, U - RoW				3.18 %
Window frame production, aluminium, U = 1.6 W/m2K | Cutoff, U - RoW	7.04 %			
Reinforcing steel production | reinforcing steel | Cutoff, U - AT	2.81 %			2.67 %
Total	80.89 %	80.99 %	80.15 %	79.74 %

Table 8
Midpoint impacts comparison between (Izaola et al., 2023) and our research, per square meter of built area.

Impact category	Unit	Izaola et al., 2023	SC 0: Brick	% variation of Scenario 0, from Izaola et al., 2023
Fossil resource scarcity	kg oil eq	889.30	446.33	50.2 %
Stratospheric ozone depletion	kg CFC11 eq	0.00	0.00	114.4 %
Global warming potential	kg CO2 eq	1913.80	1292.87	67.6 %
Fine particulate matter formation	kg PM2.5 eq	3.60	1.78	49.5 %
Human carcinogenic toxicity	kg 1,4-DCB	230.50	148.11	64.3 %
Freshwater ecotoxicity	kg 1,4-DCB	179.60	451.33	251.3 %
Water consumption	m3	64.70	57.52	88.9 %
Ozone formation, Human health	kg NOx eq	5.40	2.99	55.3 %
Mineral resource scarcity	kg Cu eq	15.60	8.45	54.2 %
Human non-carcinogenic toxicity	kg 1,4-DCB	1842.70	1898.69	103.0 %
Freshwater eutrophication	kg P eq	0.60	0.33	54.8 %
Ionizing radiation	kBq Co-60 eq	703.70	18.80	2.7 %
Marine eutrophication	kg N eq	0.10	0.04	36.3 %
Land use	m2a crop eq	35.80	44.91	125.4 %
Terrestrial acidification	kg SO2 eq	8.70	3.99	45.8 %

respective environmental impacts need to be taken into account. Global impacts such as GHG emissions or marine acidification and eutrophication should not distract us from very unequal local differences (Andersen et al., 2022).

There is a particular penalization on the rammed earth house that is fair to describe. It is unlikely that Ecoinvent's inclusion of cotton fibre flows in the LCA bill of materials comes as a first-hand product from the global market, but rather as a local reused by-product. If this were the case, burdens would actually become negative, and calculated impacts such as water consumption, marine and freshwater eutrophication, land use and fine particulate matter formation would be reduced. In addition, because the site contained radon gas, extra membranes were laid, something that the other scenarios lacked. Other studies on earthen materials (Ben-Alon et al., 2019), (Ben-Alon and Rempel, 2023), (Ajabi Naeini et al., 2021) suggest that their impacts are significantly smaller than those calculated here. However, the energy performance of this scenario as energy positive is confirmed by other studies (De Masi et al., 2021), (Lamnatou et al., 2019).

Although earth-based buildings in Spain have a long tradition, straw-bale ones were introduced in the second half of last century. However, they are gaining attention, both from the market and from scientists. There are several techniques to implement straw as structural and insulation material, and Scenario 2 cannot represent all techniques, but still, it shows results in line with other studies in Spain (Revuelta-Aramburu et al., 2020), and far beyond (Li et al., 2021). However, 75 % of the total weight of Scenario 2 is the concrete slab. Cement is still very present in all scenarios, showing its highly relevant impacts. The importance of specific materials can be seen in Tables 5, 7 and 8 above, but a substitute of cement is still largely missing. The cement industry is optimistic in relation to its challenges, but its transformation still needs to happen if it means to continue (Cembureau, 2021).

6. Conclusions and policy implication

This article shows that biodiversity impact indicators deserve greater understanding and attention in the building industry. The industry has studied its contribution to Global warming, but other Mid- and End-point impacts found in the literature review are minor. However, Terrestrial ecotoxicity, Land use and Fine particulate matter formation seem highly relevant, and are studied here. Spanish Single-Family Homes (SFH) emit 1.16 Gt CO_2eq to the atmosphere in a 50-year life cycle, of which 39.9 % is embodied in the building materials. They also impact land, water and human health with 10.2 Gt 1,4-DCB, 8.8 times more than the GHG emissions. In addition, they drive 6052 species extinct, and are responsible for 3.03 M years of life lost due to premature death or living with a disability. Divided by the 16 M people living in the Spanish SFH stock, each inhabitant lost 0.19 DALY; or 68.1 days of their lives lost. We authors are concerned that health policies disconnect human health from ecosystem health, and propose including biodiversity metrics alongside climate metrics in buildings and other industries. Overarching policies would address the habitability of all species.

When compared to the base scenario on a per m^2 basis, we found that the Earth house emitted 19,10 % GHG, the Straw home had 41.71 % embodied carbon, and the Timber SFH depleted 59.73 % mineral resources of that of the Brick house. Comparing Endpoint indicators with Scenario 0, the Earth SFH depleted 9.61 %, the Straw house three water consumption impacts averaged 10.86 %, and the Timber home carcinogenic effect was 33.93 % than that of the Brick SFH. However, on average, the three low-impact scenarios are 140 % worse in land use and 323 % in marine eutrophication impacts on species than the Brick home. On average per m^2, the Timber scenario impacts, excluding these two, are 57 %, the Straw scenario 60 %, and the Earth scenario 44 %, that of the base scenario. Concerning only ecotoxicity, the results are 48.11 %, 55.58 % and 47.09 %, respectively. Regarding biodiversity loss the impacts are 69.10 %, 67.42 % and 41.38 %, those of the Brick house. Human Health damages of the Timber home are 64.17 %, of the Straw SFH 61.96 %, and of the Earth house 46.63 % that of the Brick Scenario. But if the best solutions of the three low-impact scenarios are chosen, Midpoint impacts can be reduced by 43 % and Endpoint impacts by 40 % that of the Brick scenario. Species lost would be reduced by 56 % and DALY by 47 %. This means that biodiversity impacts of buildings can be reduced by half. We authors recommend policy makers to develop building benchmarks in this direction.

CRediT authorship contribution statement

Borja Izaola: Conceptualization, Methodology, Writing – original draft, Investigation. **Ortzi Akizu-Gardoki:** Supervision, Validation.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data available in Supplementary information.

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Appendix A. Supplementary data

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