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Urban greenhouse covering materials: Assessing environmental impacts and crop yields effects

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A B S T R A C T

Solar radiation transmissivity in greenhouses is a key property largely determined by covering materials. This study compared tomato crop yields and their environmental performance of a polycarbonate rooftop greenhouse with alternative covering materials displaying higher solar transmissivity and lifetime performance. An integrated approach using experimental data with structural, energy modeling was used to model average lifetime crop productivities. At building functional unit (per m^2·year), impacts varied between -29.0% and +24.0% compared to the current polycarbonate. Lifetime transmissivities improved up to 20.5% (4 mm-antireflective glass), leading to +46.6% of tomato yields (19.9 ± 2.2 kg/m^2), and up to -33.9% of environmental impacts. Ethylene tetrafluoroethylene 60 µm-film resulted in 19.2 ± 2.3 kg tomatoes/m^2 but improved environmental performance up to 41.7%. These results demonstrate the importance of employing integrated and life-cycle approaches to combine multiple trade-offs and dynamics within environmental assessments of greenhouse crops. The results are intended to contribute to improving greenhouse cultivation and sustainability.

1. Introduction

Greenhouse cultivation supplies around half of the worldwide fresh vegetable production (Boulard et al., 2011), providing high crop productivities all year round with efficient use of resources (e.g., land, water and fertilizers; FAO, 2018). As worldwide population increases, greenhouse footprint area increased 78.3% during the last decades (2009–2018), representing nearly 4% of the EU buildings footprint area (Eurostat, 2020). Greenhouses are not only essential to meet the increasing food demand in a growing population context by achieving improved resource-use efficiencies compared to open-field cultivation, but also as a tool to recycle waste resources within urban greenhouses, increasing cities' circularity and sustainability (Specht et al., 2013). Combining both strategies, urban greenhouses can reduce further resource-consumption in societies, thereby resulting a growing interest in the research field (Hugo et al., 2021; Jans-Singh et al., 2021; Ledesma et al., 2021, 2020). This will contribute on the future developments of greenhouse cultivation since they will be significantly influenced by environmental protection and increasing resource scarcity (Bot, 2001; Stanghellini et al., 2003), which closely relates to the water and resource use efficiency of plant photosynthesis.

1.1. The importance of covering materials in greenhouses

Solar radiation is a fundamental energy source for photosynthesis, the primary process through which energy is fixed on earth (Langhans and Tibbitts, 1997) that ultimately affects crop yields. Many authors agree that decreasing the photosynthetic active radiation (PAR) transmittance of a greenhouse cover by 1% results in respective yield reductions of 1% (Cockshull et al., 1992; Kozai et al., 2015; Papadakis

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et al., 2000). The cumulative measurement of total daily photons reached by plants is known as the daily light integral (DLI, in mol/m^2·day), and explains the linear relationship between light and plant growth rate needed to saturate the leaf net photosynthetic rate (Kozai et al., 2015). Greenhouse have the potential to enhance crop conditions to improve plant resource use (Max et al., 2012), which translates into better plant water and nutrient use efficiencies (Critten and Bailey, 2002) . This is at the expense of greenhouse infrastructure materials and reduced light transmissivities, which are both largely determined by the characteristics of greenhouse covering materials.

Both crop resource use and greenhouse infrastructures are of great importance to improve greenhouse cultivation environmental performance (Antón et al., 2014). For instance, previous studies on integrated rooftop greenhouses (iRTGs) located at the Institute of Environmental Science and Technology (ICTA-UAB, Barcelona region) showed that between 42 and 63% of global warming impacts of 1 kg of tomato were due to the greenhouse structure (Rufí-Salís et al., 2020a). The covering materials accounted for 43% of the associated impacts (Muñoz-Liesa et al., 2021a). Similarly, fertilizers used in tomato crop cycles showed a relative contribution of more than 20% to many impact categories that were analyzed (Sanjuan-Delmás et al., 2018a). Since in hydroponic cultivation fertilizers are diluted with the water used for irrigation, the amount of fertilizers is related to the crop water use efficiency (WUE). In turn, this relates with the radiation levels received by the crop, as noted by Sanjuan-Delmás et al. (2018), who reported that a spring crop had double the WUE of a winter crop. Thus, solar transmissivities achieved through greenhouse covering materials play a major role in accounting for the indirect environmental costs and the direct overall performance of greenhouse crops.

Building shadows also reduce sunlight and the DLI available for crops. This has been identified as a limiting factor for plant growth and should be addressed when urban greenhouses (Zambrano-Prado et al., 2021). Previous experiences in ICTA-iRTGs showed that 49–55% of solar radiation transmissivity was attained (Montero et al., 2017) while around 70% of solar transmissivity is commonly achieved in conventional greenhouses (Food and Agriculture Organization of the United Nations 2013). Therefore, solar radiation should be enhanced to demonstrate that the benefits of urban agriculture translate into outperformed efficiency compared to unheated greenhouses (Montero et al., 2017).

However, many technical requirements and aspects coexist during the process of selecting covering material for an urban greenhouse. These should consider material solar radiation transmissivity, insulation properties, code requirements according to their application, durability, weight or structural needs (Proksch, 2017; Sanyé-Mengual et al., 2015; Specht et al., 2013). Some of these aspects like solar transmissivity are time-dependent and specific to each covering material, and directly affect greenhouse metabolism during its entire life cycle (including plant metabolism and output yields). To this effect, all resource consumption flows and their derived environmental impacts, per unit of output yield, should be accounted for in a greenhouse's lifetime (Max et al., 2012) to later compare associated impacts for each alternative covering material that is assessed. When this is achieved, greenhouses could be optimized to provide a controlled environment that efficiently minimizes resource inputs to promote plant growth and maximize crop yields.

1.2. Towards sustainable greenhouses

European building stock, including greenhouses, will necessarily tend to zero or nearly zero emissions systems in the near future (EU, 2018; Montero et al., 2010). Hence, embodied impacts on urban assets will become increasingly important to effectively achieve low-carbon development. There is increasing interest in material usage in the built environment and it is listed as a high-relevance issue in the 5th IPCC report on climate change (IPCC, 2014). Life cycle assessment (LCA; (ISO, 2006), as an objective and qualitative methodology to assess life cycle impacts, will likely become more important in the future when sustainability issues are assessed. In fact, several studies in urban agriculture already highlight the need to adopt LCA in their environmental assessment (Mok et al., 2013; Specht et al., 2013) to quantify the environmental burdens and explore potential reductions in food production impacts (Sanyé-Mengual et al., 2015, 2012).

In this context, the objective of this paper is to assess the environmental effects of three covering materials (flat polycarbonate, single glass, ethylene tetrafluoroethylene - ETFE) that are compatible with urban greenhouses in several tomato crop cycles during their lifetime on an iRTG. For that purpose, the agronomic and environmental performance of tomato production associated with solar transmissivity lifetime losses of alternative covering materials will be quantified.

Since covering material transmissivity decays over time, the life cycle thinking perspective is important. This will allow the greenhouse infrastructure's environmental impacts to be allocated linearly to the expected tomato yields during the time frame assessed. Based on this time-dependent performance, different material replacement scenarios will be evaluated to minimize the overall greenhouse environmental impacts.

2. Methods

2.1. The iRTG case study

In this assessment, to model the impact of the six covering material scenarios that were assessed we focused on the iRTG 1 located at the top of the Institute of Environmental Science and Technology (ICTA-UAB) building (Fig. 1). The building's footprint is 36 m by 36 m and it has 7 stories, including four Venlo-iRTGs on the top floor of 128 m^2 each and a growing area of 84.34 m^2 (Fig. 1). Since its construction in 2014, multiple crop cycles have been tested (Rufí-Salís et al., 2020a). The iRTG is not actively heated and it benefits from the building waste heat and air outlets from the heating and ventilation (HVAC) system of the building, integrated next to the iRTG space. A rainwater harvesting system with 100 m^3 capacity is the main water supplier for crops. When there is not enough collected water, municipal network tap water is used. The tomato plants evaluated here were grown in iRTG 1 using a hydroponic system with perlite bags (57 bags in total), measuring 1 m long and holding 3 plants each. Nutrients are supplied with a concentrated solution mixed with water to irrigate plants through drippers (2 L/h). All these operational flows (materials, water, fertilizers, energy, window openings, indoor environment conditions or crop yields) have been manually measured or quantified through various automatic sensors (Campbell Scientific and Siemens Desigo Insight recording) to assess, control and adjust proper conditions to operate the greenhouse.

2.2. Integrating material, energy and crop assessment

The choice of greenhouse covering material is complex (Proksch, 2017). Multiple side effects and trade-offs derive from this decision, which ultimately affects greenhouse crops and their environmental performance (Fig. 2). In essence, the challenge is to establish a relationship between exterior solar radiation and the energy and crop yields obtained in the rooftop greenhouse, which are limited by the iRTG covering materials.

Keeping the same iRTG 1 geometry where tomato crops were grown, we modelled energy and crop yields derived from each scenario. To make a fair comparison, we keep the majority of iRTG variables constant, to only model the side-effects of improving covering material transmissivities (colored in Fig. 2). This required the integration of successive methods and steps to: (i) make the needed structural adaptations to ensure the assessed covering material was compatible with the current greenhouse structure as evaluated in (Muñoz-Liesa et al., 2021a); (ii) quantify greenhouse solar energy gains according to the material's lifetime performance (based on experimental data) and

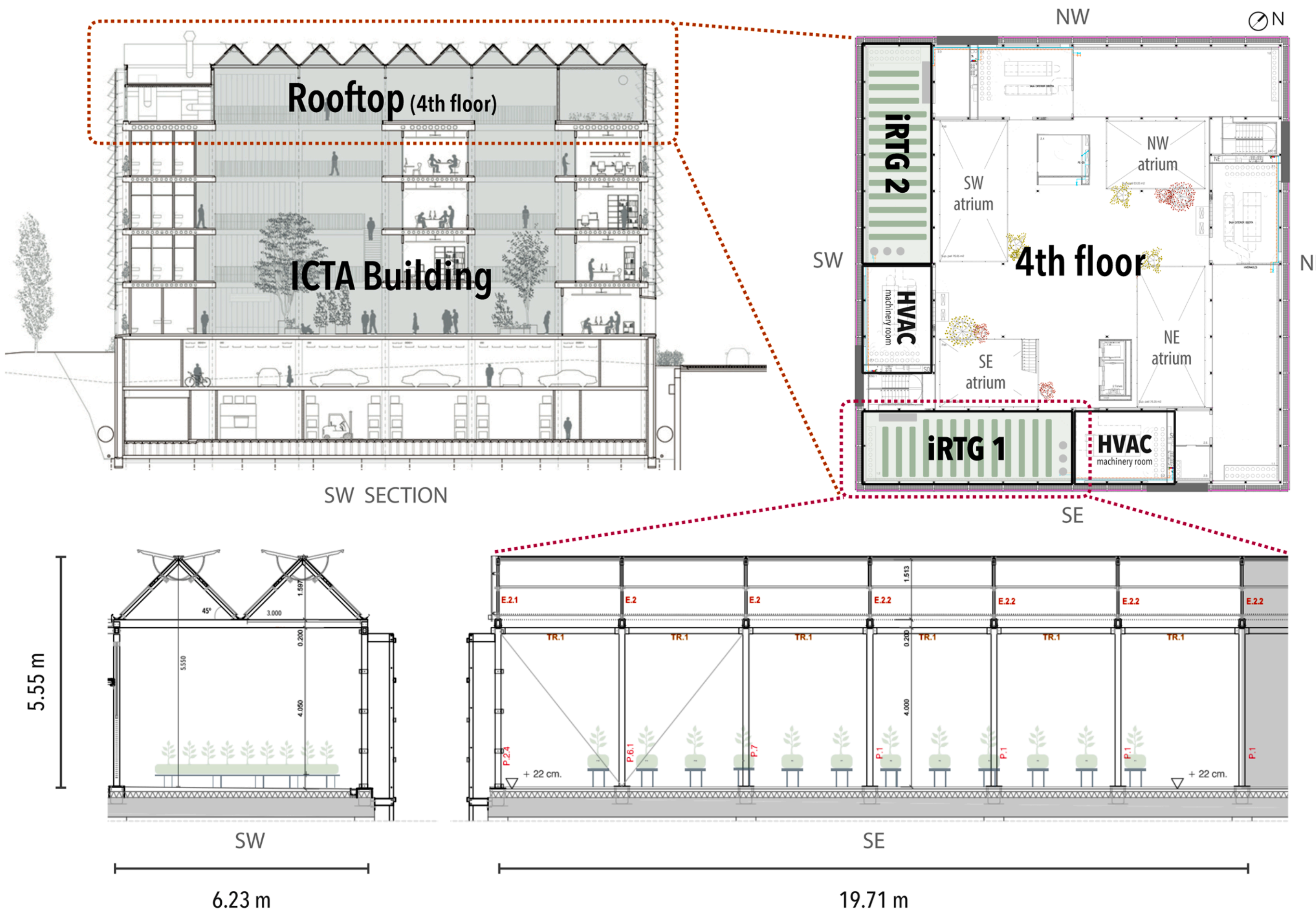


Fig. 1. ICTA-iRTG building SW section and floorplan distribution of the 4th floor including iRTG 1 geometry and SE, SW sections.

alternative covering materials through a calibrated energy model previously used in this iRTG (Muñoz-Liesa et al., 2021b, 2020; Nadal et al., 2017); (iii) quantify the photosynthetic active radiation (PAR) needed by crops compared to the PAR reached at plant canopy level, according to experimental data recorded in the iRTG (Zambrano-Prado et al., 2021); (iv) model crop output yields according to the alternative materials here assessed (Montero et al., 2017) based on several tomato crops grown in ICTA-iRTG from 2016 to 2020 (Parada et al., 2021; Rufí-Salís et al., 2020a; Sanjuan-Delmás et al., 2018a); (v) assess the environmental impacts of the entire iRTG system. Finally, iRTG crops and their environmental performance are also affected by the system's environmental boundary conditions (such as exterior outside temperature or radiation), which are integrated through experimental data inputs. All detailed explanations of these integrated methods are described in the following sections.

2.2.1. *Covering material transmissivity and lifetime assessment*

Material annual transmissivity losses were used to assess material durability during the 2015–2020 period, covering half of the 10 years of polycarbonate lifespan (BrettMartin-Ltd, 2012). Since 2015, two sensors inside iRTG (in the gutter at canopy levels) and one sensor outside the building have measured global solar radiation (Hukseflux LP02, second class pyranometer) every 5 s, recorded in average values at 10-minute intervals with a datalogger (Campbell CR3000). Then, these values were integrated in hours and intervals to calculate the daily accumulated global radiation inside (in MJ/m^2·day), compared with the equivalent value measured outside the iRTG to quantify iRTG daily solar transmissivity. This follows approaches normally considered in the literature (Castilla, 2013), which were also employed in previous studies on this case (Montero et al., 2017; Parada et al., 2021). In addition, to integrate transmissivity monthly variations, the annual transmissivity was calculated using the same procedure, in which the sum of daily solar radiation values reached inside the iRTG was divided by the equivalent outside daily measured radiation (i.e., the relationship between inside and outside in MJ/m^2·year).

2.2.2. *Energy modelling*

The solar radiation reached inside the greenhouse is modelled with an Energy Plus v9.2 model previously calibrated with temperature, relative humidity and energy consumption data (Muñoz-Liesa et al., 2020; Nadal et al., 2017). The same platform integrates the Radiance engine to calculate daylight iRTG levels and thus assess solar radiation gains achieved with different covering materials according to their optical properties. Previous modelling results showed an average of 890 kWh/m^2 of solar annual energy gains (Muñoz-Liesa et al., 2021b), which matches the reported transmissivity values of around 50% at the beginning of the polycarbonate lifetime (Montero et al., 2017).

2.2.3. *Crop modelling*

Experimental crop data used in this assessment is based on annual tomato crops (*Solanum Lycopersicum* L. *Cultivar Arawak*) grown in the SE-iRTG and previously assessed from different agronomic and environmental perspectives (Montero et al., 2017; Parada et al., 2021; Sanjuan-Delmás et al., 2018a; Sanyé-Mengual et al., 2015). Average reported crop inputs and outputs (fertilizers, water and energy consumption, emissions to water and air) were used to model actual and future yields, assuming that the same linear relationship could be established (inputs/output yields) (Montero et al., 2017).

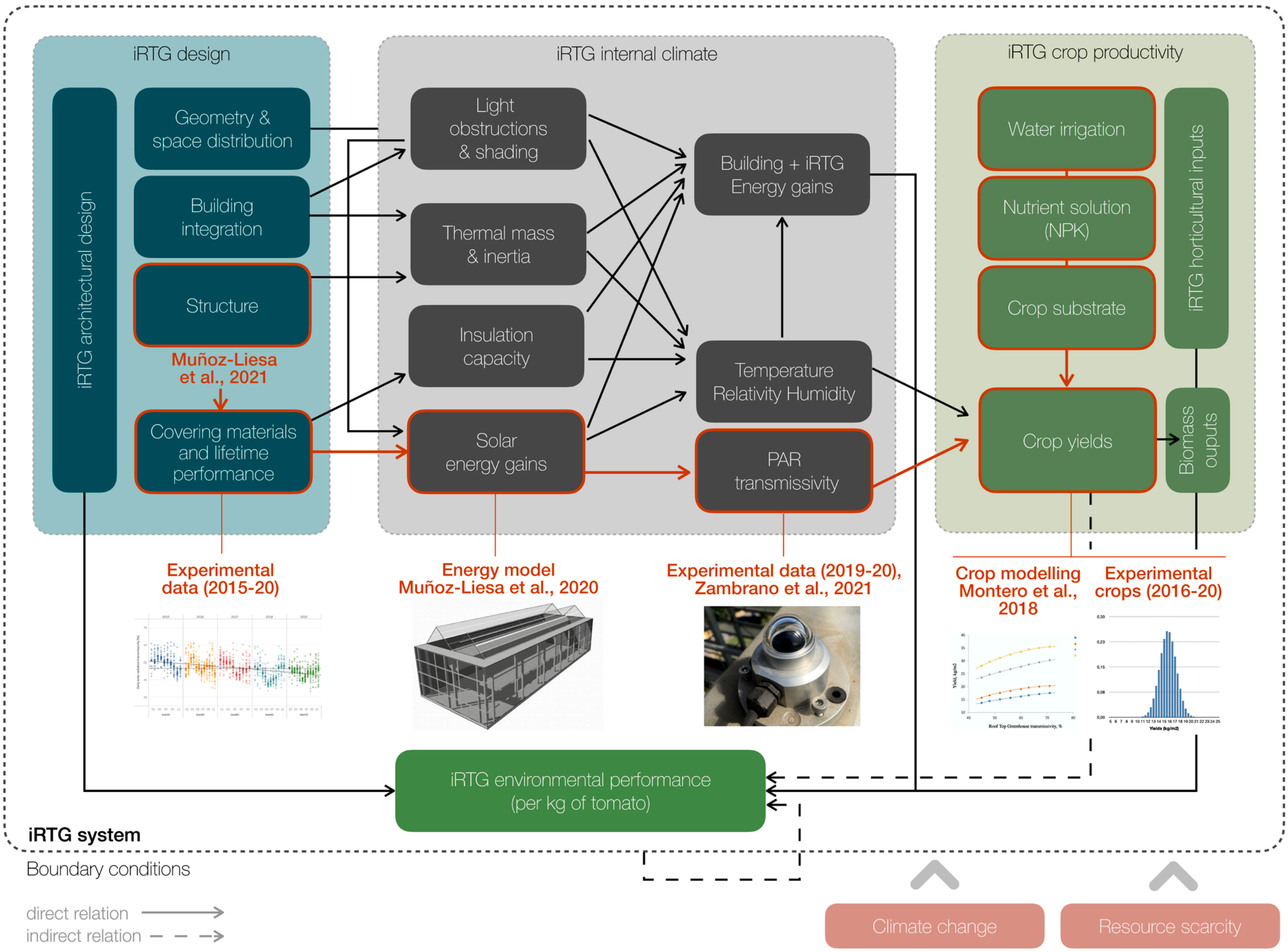


Fig. 2. Key chain reactions of covering material selection. Orange-marked variables are considered through the methods and data that are detailed, while the rest of the variables are considered constant according to the alternative materials that were assessed.

To model alternative covering materials with improved light transmissivity and yields, this study was based on (Montero et al., 2017) modelling work using the KASPRO-Vanthoor model (Vanthoor, 2011; Zwart, 1996) validated with climate and crop data yields from ICTA-iRTG 2016 spring crop. To achieve this, the authors modelled the radiation use efficiency (RUE) of tomato plants under greenhouse transmissivity values and thus quantified the effect on crop yields when iRTG light transmission improves. This gives a second-grade polynomial function ($R^2 > 0.99$) with a slope of 0.309 kg/m^2 of yield gains for each 1% transmissivity increase (Montero et al., 2017).

Since the model predicts crop productivity based on accumulated radiation during the crop period, it also integrates daily and monthly solar variability. Tomato cycle campaigns are also long enough (195 days) to be more stable in terms of accumulated radiation than other short-cycle crops (e.g., lettuce or beans). Thus, the accumulated tomato yield errors are also lower (Parada et al., 2021). In turn, the model was built to evaluate crop productivity improvements with sufficient accuracy to evaluate improvement scenarios for the iRTG design (this paper).

2.3. Hypothesis and considerations for the covering material scenarios that were assessed

Ensuring maximum solar transmissivity is a key property of greenhouse covering materials and a desirable objective at all latitudes, especially during autumn and winter (Castilla, 2013). In general, the urban environment has more technical constraints than ground-based greenhouses since they need to deal with: (i) material weight limitations according to the building load capacity and accessibility; (ii) greater light obstructions due to building shadows and greenhouse high-tech infrastructure frequently found in urban greenhouses (e.g. artificial luminaries or thermal screens, which De Zwart (1996) reported to produce 2% and 10% of greenhouse transmissivity loss, respectively); (iii) fire safety codes that apply to building envelopes, including greenhouse covering materials. For example, the Spanish Building Code (CTE, 2006) for buildings higher than 18 m does not allow façade materials with a fire classification worse than b-s3 d0, according to Euroclass standards, which range from A to E fire behavior. This implies that the common plastic materials used in conventional greenhouses or other common building materials such as acrylic glass (polymethyl methacrylate, PPMA) cannot be used in these situations, since it is labeled as E-Euroclass. Apart from the aforementioned constraints, all the materials that are assessed here have been selected to have a thermal transmittance similar to current polycarbonate material (U-value of ~6 W/m^2·K), so similar thermal and energy behavior of the ICTA and iRTG can be guaranteed. This is considered even though the improved solar transmittance of the assessed materials will increase the solar energy gains, which will likely improve the crop environment. In the case of overheating, extra heat can be conveyed through natural ventilation to achieve similar crop conditions with respect to the current situation.

Considering all the aforementioned constrains, we selected two types of polycarbonates, flat glass panes and ethylene tetrafluoroethylene (ETFE) films, all with higher solar transmissivity values to compensate for the urban greenhouse conditions and detailed characteristics as follows (Table 1). Regarding covering material maintenance, a compromise was adopted between optimized needs according to material manufacturers (annual cleaning) and current experiences based on real cases (ICTA-iRTG and Mediterranean greenhouses). For this reason, no maintenance was assumed for polycarbonate to remove dust accumulation, while two cleaning sessions in the 25 years of lifespan were considered for glass (i.e., every 7–8 years). Electricity needs for the polycarbonate maintenance process were assumed equal to the construction process that was previously reported (Muñoz-Liesa et al., 2021a). This includes energy-related costs to reach the rooftop greenhouse envelope with articulated boom lifts and scissor platforms. The dust repellent ETFE fluorinated surface had no maintenance needs in its 25 years of lifetime. Both for glass and ETFE, a conservative value for their lifetime was considered to integrate possible damage due to hail or other environmental or use damages. The detailed explanation of all scenarios can be found in the Supplementary Material.

2.4. Life cycle assessment

Life cycle assessment is a powerful tool to quantify the environmental impacts associated with products or services (ISO, 2006). LCA with an attributional approach was carried out here to compare alternative covering materials based on all related resource consumption flows, including plant metabolism changes due to increased resource use efficiency.

2.4.1. Goal and scope

The analysis considered all life-cycle stages (from raw material extraction, construction and operation to end-of-life) in each of the six colored foreground subsystem processes (covering material, energy, etc.), according to Fig. 3. A cut-off criterion was used considering that the impacts of the recycled processes were allocated to the subsequent product that benefited. To compare the environmental impacts of alternative greenhouse covering materials, two functional units were used. (i) To assess greenhouse construction impacts from the building perspective, we defined functional unit A (FUa) m^2 and year; while (ii) to assess the crop environmental performance at the production point from the agronomical perspective using a cradle-to-farm gate approach, we defined functional unit B (FUb) in kg of product (tomato). Consequently, FUb expanded the FUa system boundaries to include all materials and processes inputs needed for crop production and the corresponding outputs. Finally, an analysis of both systems was undertaken (iii) to compare differences and understand whether crop modelling should be included when greenhouse covering materials are chosen. Fig. 3 shows the main input processes and outputs involved in all life cycle stages to produce 1 m^2 per year of the iRTG structure (FUa, which included covering material and infrastructure subsystems). Similarly, in addition to FUa subsystems, energy, auxiliary equipment, the rainwater harvesting system and crop operation subsystems that were needed to produce 1 kg of tomatoes were considered.

2.4.2. Life cycle inventory

Previous inventories on this case study were used to consider the material and tomato crop inputs assessed during the 2015–2021 period. The iRTG structure was retrieved from Muñoz-Liesa et al. (2021a), updated from Sanyé-Mengual's work (2015). The iRTG auxiliary equipment was retrieved from Rufí-Salís et al. (2020a) while the rainwater harvesting system (RWHS) was based on Sanjuan-Delmás et al. (2018a). Crop operation inputs for all the assessed scenarios were calculated as described in the crop modelling section (2.2.3) and the use of perlite substrate bags, fertilizers, pesticides and water, among others, was included. Tomato crops were watered with a linear system, in which leachates were directly discharged to the sewage, despite reported approaches showing that they could be recirculated (Parada et al., 2021; Rufí-Salís et al., 2020b). Since no nutrient removal was included in the wastewater treatment process, direct emission factors to air (NH_3, NO_x and N_2O) were calculated according to IPCC standards (IPCC, 2019). Direct emissions to water were quantified in equivalent PO_4^{3-} according to data from previous assessments (Parada et al., 2021; Rufí-Salís et al., 2020a; Sanjuan-Delmás et al., 2018a).

The technical and inventory specifications of each covering material were determined according to material manufactures (EBG group, BrettMartin-Ltd). The ETFE film density of 1.75 g/cm^3 and all inventory flows were retrieved from Jungbluth et al. (2012). To calculate covering material maintenance needs, only energy inputs were assumed according to real monitored data from the ICTA building (Muñoz-Liesa et al., 2021a). The use of water or potassium soap to clean the surface or machinery use was not considered, since no maintenance has been done before. Allocation was used to account for the share of impacts of all processes that also serve the building, according to the lifespan of each process. Similarly, allocation based on water volume provided by the rainwater harvesting system was applied to distinguish between crop and building water uses (Sanjuan-Delmás et al., 2018a). The end-of-life scenario assumed all transportation inputs to the nearest facility to recycle or landfill the materials considered according to the Supplementary Material. Biomass residues were assumed to be composted in an industrial plant. All background life cycle inventory data for all processes was retrieved from the Ecoinvent database v3.8 (Ecoinvent, 2021). This material can be referred to for specific additional assumptions and information.

2.4.3. Life cycle impact assessment

Impact assessment was performed using SimaPro 9.3 software with the Ecoinvent v3.8 database. We used the ReCiPe 2016 v1.13 method at Midpoint level with a Hierarchical perspective (Huijbregts et al., 2017),

Table 1
Greenhouse covering materials, scenarios and assumptions assessed. *Annual transmissivity loss due to dust accumulation without maintenance (Montero et al., 2010). **2.4% losses for dust accumulation have been reported after 25 years of ETFE lifetime without maintenance.

Scenario	Material	Thickness	Lifetime	Material trans.	Transmissivity losses	Maintenance	RTG structural changes
S1.1	Polycarbonate	0.8 mm	10 years	83%	1.4% annually, experimental data	No maintenance, according to actual practice	Updated aluminum data from Muñoz-Liesa et al. (2021a)
S1.2	Polycarbonate	4 mm	10 years	89%			Additional steel frames for windows (equivalent to +5%)
S2.1	Single glass (uncoated)	4 mm	25 years	91%	0.5% annually due to dust accumulation*	Dust accumulation: every 7/8 years	Additional aluminum profile according to Antón et al. (2014), contrasted with aluminum content of other greenhouses.
S2.2	Single glass (AR-coated)	4 mm	25 years	98%			
S3.1	ETFE (single film)	60 μm	25 years	96%	0.15% losses over the lifetime (25 years, AGC Ltd.)**	no maintenance.	Aluminum profiles according to ebf group. these replace −5% of the current steel profiles.
S3.2	ETFE (single film)	100 μm	25 years	95%			

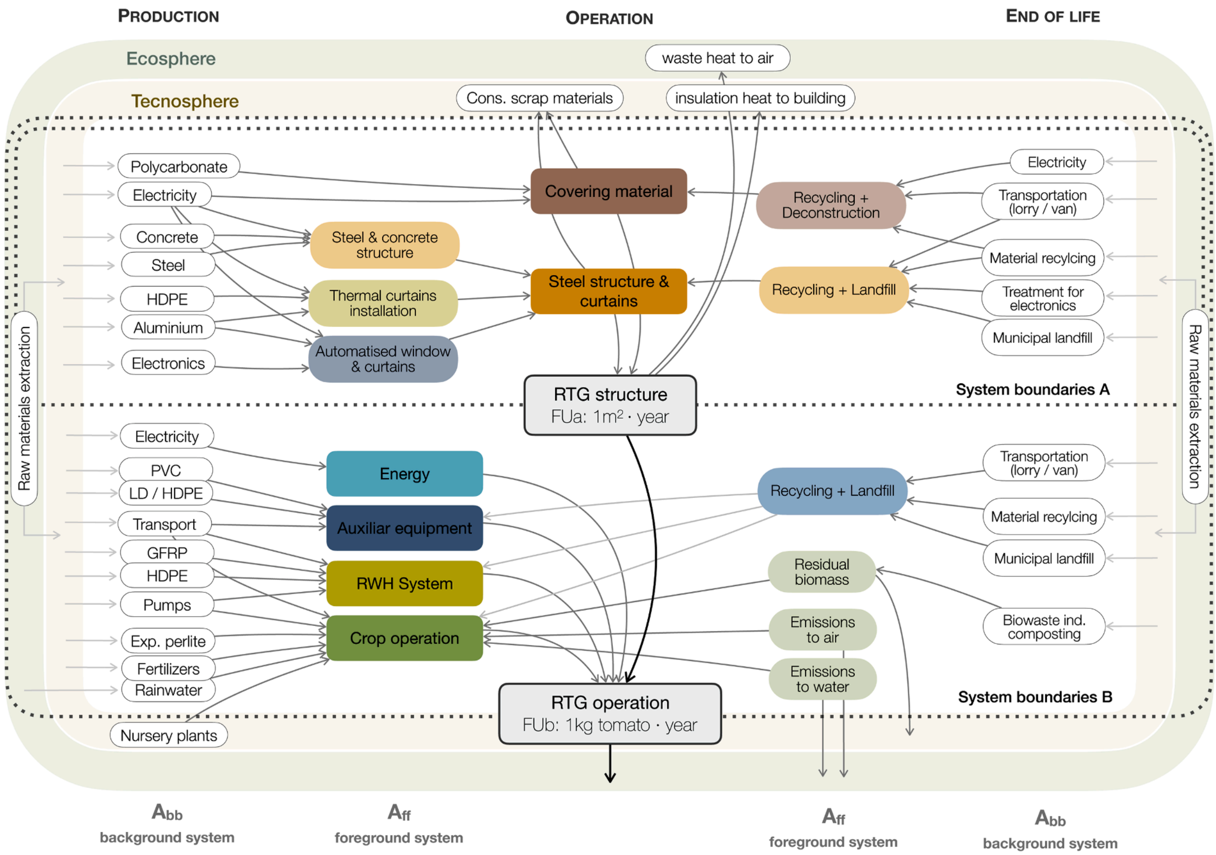
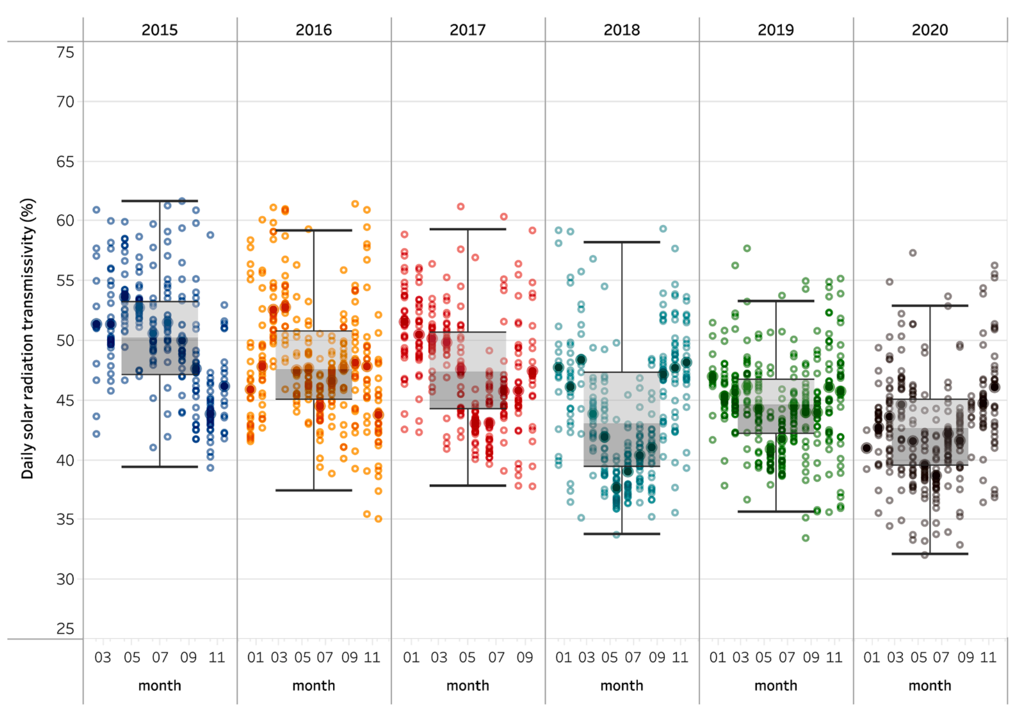


Fig. 3. System boundaries A and B for the two functional units considered. Only the main foreground (colored) and background processes (non-colored) from and to the ecosphere and technosphere are represented.



	2015	2016	2017	2018	2019	2020
Daily transmissivity (%)	50.1	48.0	47.6	43.7	44.5	42.6
Anual transmissivity (%)	50.8	47.8	46.8	42.1	44.1	40.0

Fig. 4. Average daily (colored circles and table values), monthly (colored dots and box plots) and annual (box plots and table values) transmissivity values in the ICTA-iRTG SE (iRTG 1) recorded through iRTG internal and external global solar radiation sensors.

as recommended by Amani and Schiefer (2011) to evaluate impacts on the food sector. The impact categories were selected in line with previous literature on greenhouse crops. Impacts due to building materials and fertilizers are of great concern (Antón et al., 2014; Martínez-Blanco et al., 2011; Sanjuan-Delmás et al., 2018b). According to literature on buildings and ETFE films (Cabeza et al., 2014; Lamnatou et al., 2018; Maywald and Riesser, 2016) (Cabeza et al., 2014; Rufí-Salís et al., 2020a): global warming (GW, kg CO_2 eq.), terrestrial acidification (TA, kg SO_2 eq.), freshwater eutrophication (FE, kg P eq.), marine eutrophication (ME, kg N eq.), fossil resource scarcity (FRS, kg oil eq.), ecotoxicity (ET, kg 1,4-DB eq., including marine, terrestrial and freshwater ecotoxicity) and stratospheric ozone depletion (SOD, kg CFC-11 eq.). Additionally, single-issue cumulative energy demand (CED, MJ) was added, including renewable and non-renewable energy sources. Global warming impacts were emphasized within the text to exemplify comparisons between assessed scenarios and because this is a common impact category that is addressed in literature, due to global warming concerns. All the impact category results can be found in the Supplementary Material.

3. Results and discussion

3.1. Polycarbonate lifetime as a covering material

iRTG solar transmissivity has been addressed over 6 years to assess material transmissivity during its lifetime (Fig. 4). The original solar transmissivity of polycarbonate was set at 83% (BrettMartin-Ltd, 2012), while the experimental data shows that overall greenhouse transmissivity is only 50.1% during the first year of lifetime (Fig. 4). This can be explained by the greenhouse design (roof elements) and building walls that lead to internal shadows. In addition, dust accumulation and condensation deposits on the inside reduce transmissivity since no maintenance is done in ICTA-iRTG. These deposits can cause up to a 6–7% loss in triple layer plastics (Montero et al., 2000) and could even be up to 15% in plastic films (Papadakis et al., 2000).

Transmissivity values vary across the year. Lower rates are obtained from May to August (when higher exterior radiation levels are registered) and higher rates are obtained at the beginning and the end of the year. These season variations are due to the combination of solar azimuth, greenhouse orientation (NE-SW) and roof slope (Castilla, 2013), which produces different internal shadows that are visible on the iRTG energy modelling. The daily transmissivity losses in the 2015 to 2019 period decreased at a rate of 1.4% on average per year (Fig. 4). Since lower transmissivity values occur when more exterior radiation is available, the obtained annual transmissivity loss per year of 2.2% (i.e., the amount of hourly solar internal gains compared to the exterior gains, see Section 2.2.1) is greater than the average daily transmissivity values.

These values are in line with the radiation transmissivity of polycarbonate (PC), which falls about 1–2% per year due to aging (Max et al., 2012) and up to 3.6% per year in tropical conditions, which are more adverse than temperate climate zones (Roy et al., 2000). In contrast, with the PE films that are widely used in conventional greenhouses, solar radiation transmission declines around 2–4% per year (Papadakis et al., 2000), i.e., around twice the value obtained in PC compared to the average PE. This explains the short lifetime of 3 years for PE compared to 10 years for the lifespan of PC, according to the manufacturer of the ICTA building (BrettMartin-Ltd, 2012). Thus, at the end of the PC lifetime, and assuming the same calculated linear decay of 1.4% annually, that would result in a daily transmissivity loss from 50.15% to 36.15% and an annual transmissivity loss from 50.82% to 29.12%.

3.2. Solar radiation availability versus demand

To integrate the agricultural perspective, a temporal analysis of interior and exterior solar radiation is needed, since transmissivity values and exterior radiation are both time-dependent. Similarly, the solar radiation obtained by greenhouse crops depends on their light requirements and their growing period: for tomato plants, daylight integral (DLI) needs a gradual variation from 15 to >30 mol/m^2·day (in mols of photosynthetically active photons) depending on whether they are in the vegetative or fruit phase (Schwarz et al., 2014; Spaargaren, 2001). In ICTA-iRTGs, the tomato crop season for all assessed campaigns started in mid-January and ended by the end of July, while the tomato harvest period started in April, although the crop season final yields were much higher in 2017 than in the worst campaign in 2018 (Fig. 5). This determines the vegetative and fruit phase and crop light needs, which are compared with the iRTG average monthly recorded solar radiation levels, to understand the influence of covering material throughout the year (Fig. 5).

Reported iRTG solar monthly values (converted to mol/m^2·day) are presented for 2015 and 2020 with the current polycarbonate covering (S1.1) according to the recorded transmissivity levels (Fig. 4). This resulted in 50.1% and 42.6% of iRTG transmissivity. Since the polycarbonate material has 10 years of lifetime, 2020 values correspond to half of the material lifetime and thus represent the iRTG average internal radiation values for this material. The intersection of these curves shows that the polycarbonate material does not reach the DLI targets for tomato plants during their growing period (Fig. 5). In contrast, these are almost covered if an anti-reflective glass is used, which has the highest material transmissivity levels assessed here (S2.2, resulting in 65.2% of iRTG transmissivity). Note that compared to the exterior radiation, the lower transmissivity values during late spring and summer especially penalize iRTG solar radiation levels when tomato crops require more daylight to grow their fruit. The iRTG solar radiation conditions are better for leafy crops, in which the advantages of using antireflective glass can also be shown, extending on average by 2.5 months their growing season with optimal light conditions of 14.5 mol/m^2·day. Besides, 8.5 MJ/m^2·day (equivalent to 18.8 mol/m^2·day) is established for protected agriculture (FAO, 2018; Nisen et al., 1998), which can be accomplished from mid-February to mid-October.

3.3. Potential tomato yields in the iRTG

To distinguish the impacts of the aforementioned solar decay with annual tomato productivity variations obtained during the four tomato crop campaigns assessed here (2016, 2017–2019), the productivity values were modelled (Montero et al., 2017) as if they were all performed in the first year of the PC lifetime, when maximum tomato productivity was achieved. Hence, the same transmissivity values were assumed (50.2%) for all campaigns by modelling crop productivity rates according to transmissivity differences obtained during these campaigns. An average maximum productivity of 15.70 ± 1.54 kg/m^2 of tomato yields was obtained with an average radiation use efficiency of 7.71 ± 1.18 g of fresh tomato fruit weight per MJ of accumulated exterior radiation (Table 2). This is similar to the 7.78 g/MJ found in tomato crops grown in conventional unheated greenhouses (Montero et al., 2017) and lower than the modelling values (8.77 g/MJ), as they tend to overestimate crop productivity since no pests or diseases are considered (Montero et al., 2017). Moreover, crop managers and practices varied over the years, and these might not be fully optimized to reach such values. To compare the relevance of these experimental values, the application of the crop model RUE together with the modelled solar radiation (using a Monte Carlo analysis of 5000 iterations) produced higher potential yields (17.90 kg/m^2). This also gave theoretical solar and yield variations that were lower than the experimental data (3.9% vs. 9.0%, Table 2). Thus, a conservative value of 15.70 ± 1.54 kg/m^2 was adopted to extrapolate crop yield variations during the lifetime transmissivities expected for each of the studied covering material scenarios.

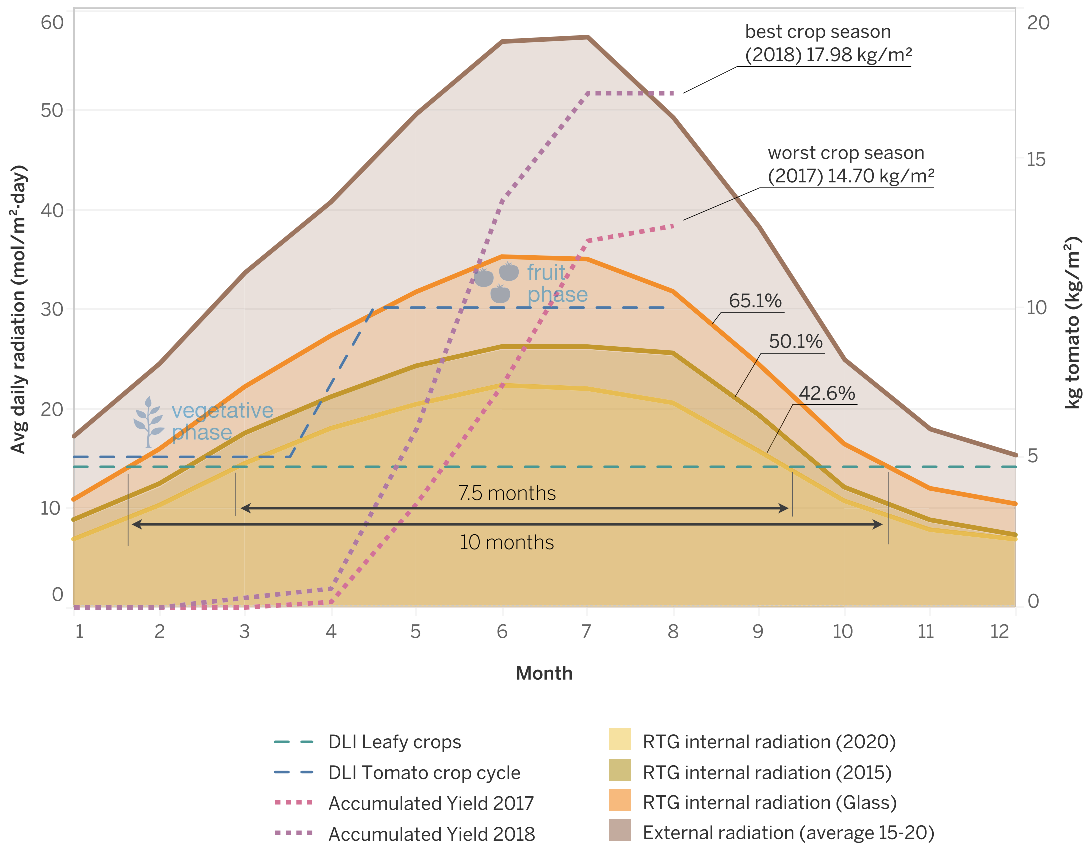


Fig. 5. Average daily solar radiation reached inside the greenhouse for the current polycarbonate material (S1.1, yellow/brown lines, measured in mol photons/m^2·day) according to monthly transmissivity values during the 2015–2020 period and the calculated solar levels reached for an AR-glass covering (S2.2, orange line). Accumulated tomato yields from the best and worst crop seasons (red-dotted lines) determine the vegetative and fruit phase of tomato plants and their respective daylight integral (DLI) needs (blue-dotted line).

Table 2
Experimental-based and modelled solar external radiation with productivity values for tomato crops under 50.1% of transmissivity rate.

Scope	Number of crop campaigns / iterations	Average. External radiation (MJ)	Standard deviation. External radiation (MJ)	Average. Productivity (kg/m^2)	Standard deviation. *Productivity (kg/m^2)*	Average. Radiation use efficiency (RUE)
Experimental	4	3654.7	207.4	15.70	1.54	7.71
Modelled	5000	3641.1	76.0	17.90	0.67	8.77

3.4. Energy and tomato yields for each scenario

Using the same crop model, tomato productivities were calculated for each of the studied scenarios (and according to their lifetime solar transmissivity, Table 3). The energy calibrated model proved that material transmissivity has a linear relationship with greenhouse solar gains, which implies that each 1% of increased transmissivity produces 1% more than the original polycarbonate solar gains (set at 50.2% for year 2015, Fig. 4, see Supplementary Material for additional energy modelling results). The transmissivity differences throughout the polycarbonate lifetime of S1.1 produce yield variations from 15.70 to 13.56 kg/m^2 (which is higher than the standard deviation of 1.54 kg/m^2), while the minimum obtained yields after 25 years of lifetime for scenarios 2 and 3 are below their standard deviation. On average, both S2 and S3 yields increased more than 1.4 times the obtained S1.1 yields. Other reported literature comparing glass and ETFE film with conventional covering materials also showed an increase in crop yields and differences in plant physiology (He et al., 2021; Montero and Antón, 2003).

The irrigation water use efficiency (WUE, understood as input water

Table 3
Modelled solar external radiation and tomato productivities during the iRTG lifetime (first year, end of life, average lifetime values) for all covering material scenarios assessed, including water use efficiency (WUE) and radiation use efficiency (RUE) modelled values.

		iRTG transmissivity (%)			Tomato yields (kg)				
Scenario	Material	First year	EoL	Average	First year	EoL	Average	WUE (L/kg)	RUE (g/MJ)
S1.1	Polycarbonate	50.1	36.2	43.2	15.70	11.52	13.56	50.72	6.64
S1.2	Polycarbonate	56.1	42.6	49.4	17.55	13.37	15.46	44.47	7.58
S2.1	Single glass (uncoated)	58.1	57.7	56.7	18.17	18.02	17.72	38.80	8.68
S2.2	Single glass (AR-coated)	65.1	64.7	63.7	20.33	20.18	19.88	34.58	9.74
S3.1	ETFE (single film)	63.1	59.6	61.4	19.71	18.60	19.16	35.89	9.39
S3.2	ETFE (single film)	62.1	58.6	60.4	19.41	18.29	18.85	36.43	9.24

irrigation demand, in L, per output yields, in kg) achieved for these tomato yields was up to 34.58 L/kg. This is a realistic value considering that other WUE values achieved in unheated greenhouses are 21–43 L/kg, improved up to 15–23 L/kg in heated greenhouses (FAO, 2013). WUE values achieved in open-field tomatoes cultivated on soil are much worse, ranging from 59 to 125 L/kg (FAO, 2013), which underlies the benefits of protected cultivation. Calculated RUE levels are also lower than potential estimations of 10.99 g/MJ and 13.21 g/MJ with CO_2 enrichment (Montero et al., 2017), which point to the potential improvements in greenhouse cultivation integrated with CO_2 waste from cities. Overall, the increased productivity will enhance multiple ecosystem services (by providing fresh and local food but also by greening spaces and lowering temperatures) that urban agriculture offers to cities (Langemeyer et al., 2021).

3.5. Impact assessment

3.5.1. Functional unit analysis and comparison

Fig. 6 shows the impact contribution in the global warming category for each studied scenario, to illustrate the differences between functional unit A (FUa, per m^2 and year of greenhouse) and functional unit B (FUb, per kg of tomato). In FUa, compared to the baseline scenario (S1.1), the impact result reductions vary from −1.6% to −13.0% in S3.2 and S3.1 respectively. In contrast, the lack of inertia of flat polycarbonate (PC) compared to current corrugated PC increase the amount of material needed and thus the GW impacts to +110% (note y-axis has a blank gap), while the rest of the impact categories increase from 8.9 to 125.7%. GW impact results across all scenarios share a similar pattern to CED and FRS impact categories, varying from +112.1 to −29.0%. Scenarios 2.1 and 2.2 increase TA, ET, FE and ME impacts particularly, due to glass and aluminum profile-derived impacts, while these were all reduced from −0.6 to 18.3% in scenarios 3.1 and 3.2. See the Supplementary Material for a detailed comparison across all impact categories and scenarios.

Although the total impacts do not show significant differences, contribution analysis reveals differences in (i) material impacts, (ii) covering construction and operation impacts, and (iii) the impacts of the steel and aluminum frames required to attach covering materials. The construction and operational impacts related to glass are greater than in other scenarios, since ETFE benefits from the dust-repellent effect. These energy requirements are important in rooftop agriculture as rooftop greenhouses require up to 7.2 times the energy needed to build ground-based greenhouses (Muñoz-Liesa et al., 2021a).

Aluminum profiles contribute more in S2 and S3. However, this does not compensate for the reduction of impacts from having few steel frames in S3 due to the lightweight ETFE. This might be because the dimensions and design of ICTA-iRTG do not allow further lightening of the window frames for the covering material by increasing truss spacing up to 2.5 m. The current space between supports is 1 m. An increase in truss spacing would reduce the number of aluminum profiles, which have a considerable environmental contribution, despite their relatively low material amount compared to steel (0.825 vs 0.066 kg/m^2). The structural advantages of ETFE film compared to glass as a covering material (Maywald and Riesser, 2016) might be more beneficial in other building environments (and open spaces in ground-based greenhouses) than in the case study assessed here (Maywald and Riesser, 2016). Finally, steel and aluminum inputs for the iRTG structure are compensated due to the expected greater lifetime of iRTG (50 years compared to the 25 or 15 years that is normally considered for conventional greenhouses (Antón et al., 2014; CEN, 2019, 1991)) while covering materials do not always benefit from these, due to their shorter life spans.

This assessment also reveals a disparity of results, when 1 m^2 of covering material is assessed (light orange in Fig. 6) compared to FUa (1 m^2 of greenhouse), since the latter integrates all associated side-effects and the life cycle building costs of each material. Similarly, greater differences occur at FUb than FUa, where except for S1.2 and SOD impacts, the rest of impacts and scenarios ranging from +29.0 to −24.0% of differences compared to the S1.1 scenario were all reduced from −17.6 to −39.7%. An example of this is global warming impacts (Fig. 6) that were cut from 13.0% in FUa to 33.9% in FUb (S3.1, ETFE film 60 μm) and up to 33.4% in S2.2 (anti-reflective glass). This is because FUb impacts capture the crop productivity values expected for each studied scenario (Table 3) and thus improve the overall greenhouse resource-use efficiency of crop production. Other urban agriculture studies highlight the influence of crop yields on environmental metrics (Weidner et al., 2019), which greatly vary considering the multiple non-commercial

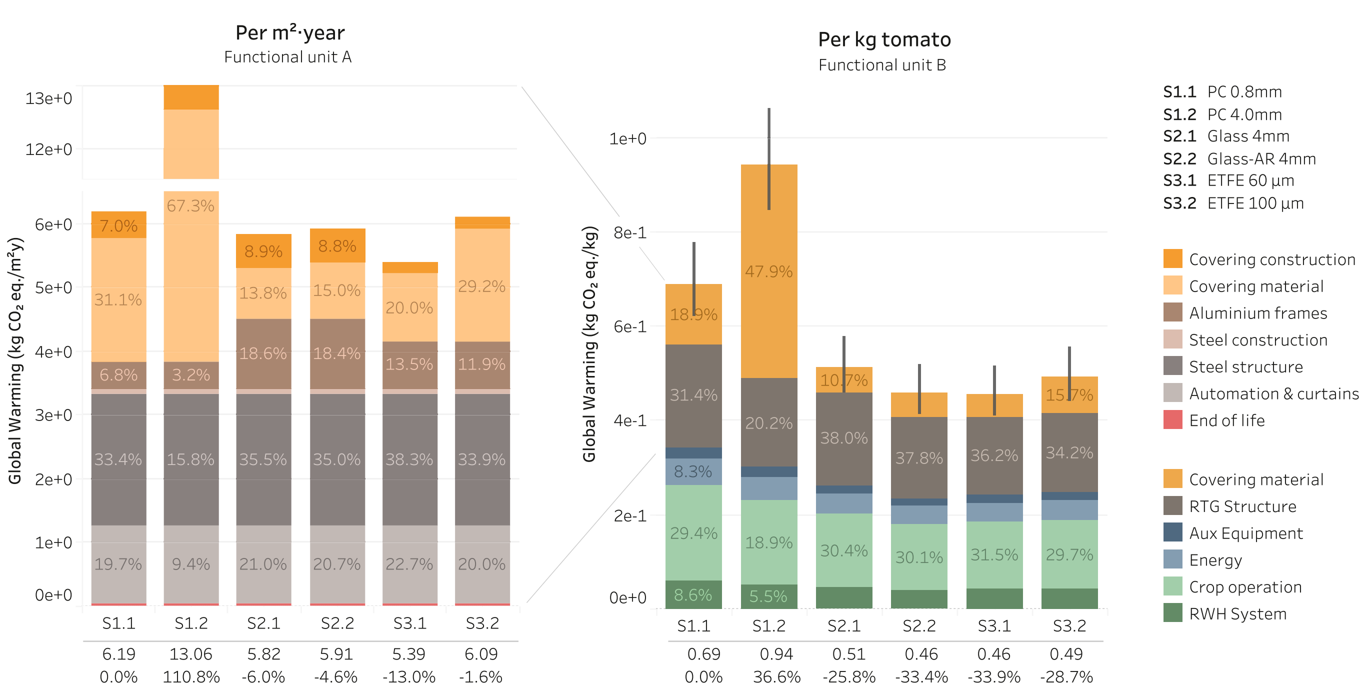


Fig. 6. Global warming impacts per functional unit A (m^2·year of greenhouse) and B (kg of tomato) for all assessed scenarios compared to the S1.1 scenario. Color bars represent each analyzed subsystem. See the Supplementary Material for an assessment of the rest of impact categories.

proposes and actors in UA. This also helps to compensate for S1.2 impacts although they are still 36.6% greater in the GW category than in the baseline scenario. Please see the Supplementary Material for further details.

3.5.2. Tomato crop impacts

In absolute terms, global warming results illustrate the decrease in impacts from 0.69±0.08 kg CO_2 eq./kg of tomato (S1.1) to 0.46±0.05 kg CO_2 eq./kg of tomato (S3.1) on average (Fig. 6). Error bars in Fig. 7 also show the standard variations of impacts according to crop yield variations, based on Section 3.3 results. The output values are much lower than previous literature on heated greenhouses (up to 0.97 kg CO_2 eq./kg of tomato) and close to the impacts shown in unheated greenhouses (0.37 kg CO_2 eq./kg of tomato) (Ecoinvent, 2021). This is not surprising, considering that iRTGs are not actively heated as they benefit from building waste heat.

Environmental scores for all the assessed impact categories showed a similar pattern to global warming impacts in CED, FRS and TA, in which impacts were reduced from 33.9% to 39.7% in the best scenario (S3.1) compared to S1.1 (Fig. 7). Eutrophication impacts (FE, ME) greatly rely on the fertilizers used in tomato crops and thus showed a different pattern, with a 29.6 and 31.4% reduction respectively in S3.1 compared to the baseline scenario. Ecotoxicity impacts were also reduced up to 30.0%. Finally, environmental shifting exists between the impact categories analyzed in the stratospheric ozone depletion impact category due to emissions caused by tetrafluoroethylene production used in ETFE. This caused 41.7% increased impacts compared to the S1.1 scenario. No other chlorinated or fluorinated carbons were released at the production step of tetrafluoroethylene to later produce ETFE (Jungbluth et al., 2012).

At both functional levels, ETFE film (S3.1) showed slightly improved environmental performance compared to other scenarios in most of the assessed impact categories. Despite this, 100 μm film (S3.2) might be convenient in most applications (due to higher environmental loads) and is a standard thickness for this material. In comparison, AR-glass still has good performance. Importantly, within the impact categories assessed here, tetrafluoroethylene production covered between 84.4 and 100% of ETFE impacts. Since the impacts of this process were much higher in previous Ecoinvent versions (up to v3.3) (Ecoinvent, 2018), ETFE impacts were also higher in previous assessments. For instance, GW impacts were 2.36 times greater in v3.3 than in v3.4 and above, which makes ETFE an inappropriate material from an environmental perspective.

While the results are based on average productivities for each material lifetime performance, environmental impacts in S1.1 would result in crop yields that impact between 0.60 and 0.81 ± 0.08 kg CO_2 eq./kg of tomato through the greenhouse's lifetime. Since the covering material decay is less for ETFE and glass, smaller environmental differences exist. This fact should be taken into account in plastic ground-based greenhouses, considering that the transmissivity of PE films declines over its lifetime (~3 years) by around 2–4% per year and 5–6% per year in EVA films (although their PAR transmissivity is slightly higher than PE films, Papadakis et al., 2000). This helps to understand the context of crop environmental assessments in which building material time factors are not normally considered, whereas they are representative of the average expected performance within the covering material lifetime.

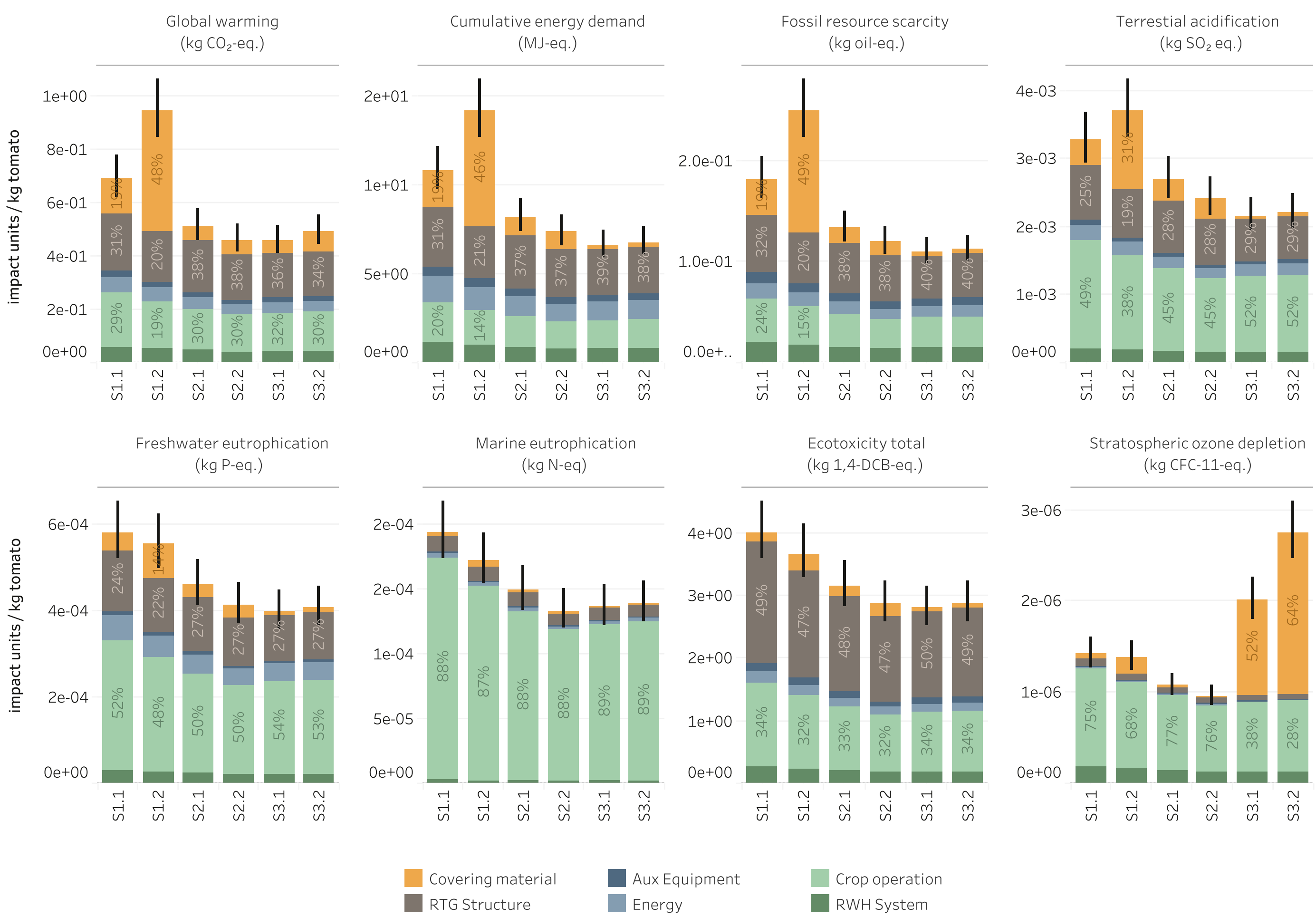


Fig. 7. Environmental score and standard error for each impact category were analyzed per functional unit B (kg of tomato). Color bars represent each subsystem that was analyzed.

3.6. Final remarks

3.6.1. Preliminary assessment of leafy crops

The integrated approach described here largely depends on crop light needs and the purpose of greenhouse cultivation. As noted in Fig. 5, leafy crops require a constant (assumed constant considering their short growing cycle) daylight integral (DLI) of 14 mol/m^2·day. While this value is exceeded during the summer period, during the winter it constitutes a bottleneck for plant growth, as DLI are lower than 14 mol/m^2·day according to the chosen covering materials. Again this will worsen plant resource use efficiency and productivity, and produce worse environmental performance too. For instance, on average, an AR-glass will increase the optimal cultivation period from 7.5 to 9 months per year compared to the current polycarbonate material. Therefore, if the greenhouse's main function under assessment is to produce leafy crops all year around, the covering material that is chosen might be a limitation. In contrast, if the objective is to produce leafy crops during the summer (or any other crop such as leafy greens requiring less DLIs), all materials here assessed would provide similar yields.

3.6.2. Limitations of the study and further research

The assessment performed is intended for alternative covering materials with an environmental perspective and a cut-off approach. Three important issues remain unsolved and should be accounted for:

(i) An average of 28.4% of the annual solar radiation is lost due to internal shadows caused by building infrastructure and iRTG elements. This factor must be taken into account from an architectural viewpoint, in addition to the assessment conducted, since shadows clearly hamper crop response (Montero et al., 2017). Further research is also needed to account for the energy implications within the ICTA-iRTG system of the increased solar energy gains here quantified (20.5%).

(ii) Experience in ICTA building shows that the economic costs of maintenance are up to 6.10 €/m^2 of covering material, while the material costs (without labor) are around 5 €/m^2 for single glass and 16 €/m^2 for corrugated PC and AR-coated glass (Max et al., 2012). This explains why no maintenance has been done, since it is not economically feasible, and why conventional-greenhouse plastic films are replaced every 3 years rather than maintained. A possible solution is to combine a very thin layer of fluorinated materials (such as ETFE or PTFE, (Stefani et al., 2008) with other covering materials (e.g., the AR-glass assessed here) to take advantage of the dust-repellent effect without compromising the material's solar transmissivity too much (He et al., 2021). The life-cycle approach employed here could allow further optimization of the replacement strategies during iRTG lifetime that minimize greenhouse crop environmental impacts, considering overall greenhouse performance.

(iii) Finally, the output biomass residue (leaves, stems and roots) for all assessed crops was also dependent on greenhouse transmissivity and was integrated into the system boundaries. This biomass waste is treated in an industrial composting plant and does not account for relevant additional environmental impacts with the cut-off perspective. However this represents an indirect measure of plant efficiency and a residue that needs to be handled and thus minimized. The average amount of waste biomass in the ICTA-iRTG tomato spring crops assessed here is 0.34 kg/kg of tomato but could be up to 3.2 higher in winter tomato crops, when very lower solar radiation levels are recorded (Sanjuan-Delmás et al., 2018a).

4. Conclusions

Solar radiation is an essential factor in plant growth and directly impacts crop productivity and overall greenhouse environmental performance. This paper assessed greenhouse covering materials suitable for urban agriculture to quantify the global environmental performance of the resulting crop yields, taking into account the corresponding infrastructure. We performed an integrated assessment to account for the multiple side-effects of six covering materials within two functional units to understand the building and agronomic implications.

We demonstrated that environmental impacts of a single 4 mm-glass and a 60 µm-ETFE film at building functional level (per m^2 and year) caused a shift of $-29.0\% - +24.0\%$ in 7 out of the 8 impact categories analyzed compared to the current polycarbonate material. The improved average lifetime transmissivity up to 20.5% with an antireflective (AR) glass led to a 46.6% increase in the average lifetime tomato productivity (19.9 ± 2.3 kg/m^2), while 19.2 ± 2.2 kg/m^2 were obtained with a 60 µm-ETFE film. The environmental impacts per kg of tomato decreased by up to 41.7% and 33.9% with an ETFE 60 µm-film and the 4 mm-AR glass covering, respectively, which contrasts with the results for the building functional unit. This could shift the global warming impacts to 0.46±0.05 kg CO_2 eq./kg of tomato (ETFE 60 µm-film), which is almost half of the impacts found in heated conventional greenhouses.

We therefore recommend the use of AR-glass and ETFE film for tomato crops, while polycarbonate material could be more suitable for leafy crops requiring less solar radiation to grow. These results highlight the importance of employing integrated and life-cycle approaches to account for multiple side effects in different functional units, while considering the effect of greenhouse dynamics within crop environmental assessments. In turn, this will improve greenhouse cultivation and circularity in urban environments, enhance ecosystem services, reduce plastic waste from plastic-covered greenhouses and improve the environmental sustainability of urban agriculture

CRediT author statement

All authors were responsible for the conception of the study, writing review & editing. J. Muñoz-Liesa, F. Parada, D. Volk Investigation, Resources; J. Muñoz-Liesa Software analysis, Data Validation, Life Cycle Assessment analysis, Writing and leading original draft, Data curation, Visualization; E. Cuerva, S. Gassó-Domingo, A. Josa, T. Nemecek Supervision, Project administration, funding acquisition. J. Muñoz-Liesa, F. Parada, E. Cuerva, S. Gassó-Domingo, A. Josa, T. Nemecek critically revised the draft for important intellectual content. All authors gave their final approval to the manuscript.

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, The authors declare the following financial interests/personal relationships which may be considered as potential competing interests

Data Availability

Please see online supplementary data for detailed inventory and results.

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Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.resconrec.2022.106527.

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