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The importance of biogenic carbon storage in the greenhouse gas footprint of medium density fiberboard from poplar wood and bagasse

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ABSTRACT

Carbon storage in long-lived bio-based products is typically ignored or accounted for in a simplistic way in greenhouse gas (GHG) footprint calculations. We quantified the GHG footprint of medium density fiberboard (MDF) in Iran from poplar wood and bagasse, a by-product from sugarcane production. Inventory data was collected from sugarcane and poplar wood plantations and MDF factories in Iran during 2017–2019 to calculate cradle-to-grave footprints for 1 m^3 of MDF. We quantify the effect of carbon storage, which depends on the crop rotation time and the economic lifetime of the product, with shorter rotation times and longer storage periods leading to lower footprints.

Cradle-to-grave GHG footprints of poplar and bagasse-based MDF without accounting for biogenic carbon storage are $6.8 \cdot 10^2$ kg CO_2-eq/m^3 and $8.5 \cdot 10^2$ kg CO_2-eq/m^3, respectively. Footprints are higher for bagasse-based MDF than for poplar-based MDF because of a higher electricity use, higher resin use and larger transport distances in Iran. Taking into account carbon storage periods of 10–60 years decreases the footprints to 345–655 kg CO_2-eq/m^3 for poplar-based MDF and 292–771 kg CO_2-eq/m^3 for bagasse-based MDF. These results emphasize the importance of appropriately accounting for biogenic carbon storage in GHG footprint calculations of long-lived bio based products.

1. Introduction

Increasing biomass utilization may substantially contribute to climate mitigation. For instance, the use of biomaterials in the construction sector can avoid the use of fossil energy-intensive alternatives such as concrete and steel, while the material simultaneously acts as a temporary anthropogenic carbon sink (Hafner and Schäfer, 2018; Peñaloza et al., 2018; Wang et al., 2018; Churkina et al., 2020). It has been estimated that carbon storage can annually eliminate 424 million tonnes of carbon dioxide (CO_2) from the atmosphere (Miner, 2010).

There are multiple ways to include the effect of biogenic carbon storage in Life Cycle Assessment (LCA) studies that vary in complexity. Brandão et al., 2013 evaluated six methods for assessment the impact of storing biogenic carbon. Non-dynamic approaches are approaches that do not consider the time of emission/storage. Among the methods assessed were the Moura-Costa technique (Moura-Costa and Wilson, 2000) and the Lashof method (Fearnside et al., 2000). Both were also considered in the IPCC report about land use and forestry (Watson et al., 2000). The (original) PAS 2050 method (BSI PAS 2050, 2008) treats biogenic storage as a delayed emission of CO_2, where the delayed emissions can be subtracted from the final results. Only the first 100 years are considered, all emissions that are delayed (i.e. stored) by more than 100 years are not included. A similar but somewhat simpler approach was proposed by the ILCD (European Commission, 2010). According to this approach delayed emissions can be included for a period up to 100 years, with a factor of −0.01 kg CO_2 eq/kg CO_2 multiplied by the number of years an emission is delayed, i.e. if the storage period is 50 years, a factor of −0.5 kg CO_2 eq may be assigned to the stored CO_2. As opposed to these non-dynamic methods, GHG emissions and storage can also be tracked through time in a procedure called dynamic LCA. Dynamic LCA can consistently apply the correct GWP to each emission/sequestration (Levasseur et al., 2010, 2013), but requires a temporally specific life cycle inventory, which may not be easily acquired. After assessing these six methods Brandão et al., 2013 conclude that the results partly depend on value judgements (especially around the chosen time horizon) and

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therefore they do not recommend a preferred method. It is also clear however that the methods vary greatly in complexity and flexibility. An alternative, flexible but relatively simple, method to determine the effect of biogenic carbon storage was originally developed by Cherubini, 2010. This approach was updated by Guest et al., 2013a, 2013b, who supply characterization factors for different combinations of crop rotation times and economic life times, which can be used in the assessment of bio-based building materials. This method has the advantage of being flexible enough to differentiate between fast- and slow-growing crops and economic lifetimes, like dynamic LCA, but still being relatively simple to use in combination with a standard life cycle inventory.

Inclusion of biogenic carbon storage in the assessment of building materials in one form or another has found its way into the assessment of long-lived wood based products (Fouquet et al., 2015; Pittau et al., 2018, 2019; Nakano et al., 2018, 2020; Head et al., 2019; Zhang et al., 2020). Peñaloza et al., 2018 used dynamic LCA to take into account the biogenic carbon storage in wood based bridges and indicated that the way CO_2 uptake is modelled and the considered time period are main factors in the calculation. Temporary carbon storage in wood buildings and wood based construction is a major determinant of the carbon footprint of these products (Tellnes et al., 2014, 2017; Garcia et al., 2020).

A widely used wood-based construction material is Medium Density Fiberboard (MDF), this material is composed of fine lignocellulosic fibers bonded with synthetic resin under heat and pressure. MDF finds its most common use in furniture, kitchens and offices cabinets (Food and Agriculture Organization of the United Nations, 2019). Several studies quantified the GHG footprint of MDF produced in various countries, including Spain, China, Brazil and Iran (Wang et al., 2018; Nakano et al., 2018; González-García et al., 2009, 2011; Wilson, 2010; Piekarski et al., 2014, 2017; Kouchaki-Penchah et al., 2016; Puettmann et al., 2016; Yuan and Guo, 2017; Athena Sustainable Materials Institute, 2013). In none of these studies, however, the biogenic part is adequately taken into account from a full life cycle perspective. Depending on the scope of the study, biogenic carbon may or may not be included. In most footprint studies, the biogenic carbon in MDF is not included (Wang et al., 2018; Nakano et al., 2018; González-García et al., 2009; Piekarski et al., 2014; Kouchaki-Penchah et al., 2016; Yuan and Guo, 2017; Athena Sustainable Materials Institute, 2013), while other studies subtracted the biogenic carbon in MDF from the fossil GHG emissions in the MDF life cycle, leaving the eventual release of biogenic carbon at the end of the life time of MDF out of the scope of their analysis (Wilson, 2010; Piekarski et al., 2017; Puettmann et al., 2016).

Besides traditional forestry biomass, the feedstock for MDF can also be sourced from purpose-grown biomass in the form of fast-growing trees, like Poplar (*Populus* spp.), or lignocellulosic agricultural biomass residues from annual crops like wheat straw and bagasse (a by-product from sugarcane production). Studies into the mechanical properties of bagasse-based particleboards have demonstrated its feasibility as a feedstock for particleboard production (Basta et al., 2017; Nakanishi et al., 2018; Milagres et al., 2019). The panel production and transport phases were identified as potential hotspots for environmental impacts (dos Santos et al., 2014; Silva et al., 2014). MDF factories in low forest-cover countries such as Iran are increasingly using these alternative sources (Akgül et al., 2010; Azizi et al., 2020). In order to adequately calculate the GHG footprint of MDF a method that can incorporate different crop rotation times and storage times in the economy is needed. In this study we therefore quantified the cradle-to-grave GHG footprint of medium density fiberboard production from poplar wood and bagasse in Iran using the GWP_{bio} factors developed by Guest et al. (2013a).

2. Materials and methods

2.1. Goal and scope

The goal of this study was to compare the GHG footprint of MDF made from two different source materials (poplar and bagasse), with and without taking into account biogenic carbon storage scenarios. The functional unit (FU) in our study was the use of 1 m^3 of finished and uncoated MDF in construction. Carbon storage periods of 10 up to 60 years are taken into account with 10 year intervals, whereby a storage period of 40 years is used as the default. The moisture content of the finished board was approximately 7% after oven-drying. The average thickness of the panels produced and their average density was 17.4 mm and 725 kg/m^3 respectively on an oven-dried weight basis for bagasse-based MDF. Two types of lignocellulosic biomass sources were included; poplar wood, produced in the western part and bagasse from sugarcane production, produced in the south-western part of Iran (see Fig. 1). Related data about raw material extraction, transportation, MDF manufacturing, product distribution, product use and the end of life was collected by interviews with farm owners, MDF factory managers and the sugarcane agro industries and the research institute of forests in Iran.

The foreground data of the MDF life cycle inventory were obtained from an on-site survey and questionnaires of one sugarcane and one poplar wood plantation with areas of 28000 and 10000 ha respectively, and two MDF factories (one using bagasse and one using poplar as feedstock). The data collection was done for two years during 2017–2019. For biomass production inputs and outputs include energy (e.g. fossil fuel, main machinery used for planting and harvesting poplar wood and sugarcane) and raw materials such as manure, pesticide and herbicide and for MDF production inputs and outputs include energy (e.g. fossil fuel, electricity, natural gas and etc.) and material (wood or bagasse and chemical materials such as UF resin, ammonium chloride and etc.). Life cycle inventory data related to the background system were based on the Ecoinvent 3.6 database (Wernet et al., 2016).

2.2. Production of poplar-based MDF

The system boundaries for poplar-based MDF production are shown in Fig. 2. Poplar (*Populus nigra*) seedlings were planted with a spacing of 300 cm along the rows and with 300 cm between the rows. The number of trees was 200 per hectare and the final planting weight of wood was 1.84 tonne per hectare. The rotation time of poplar wood to produce MDF is typically 12 years in the two northern regions of Iran. The poplar based MDF factory has an average annual production volume of 114,000 m^3 MDF. This factory uses poplar round wood and a smaller share of garden trees waste pruning. The production of the garden waste itself is considered outside the system boundaries of the MDF life cycle.

Fiber preparation starts with the preparation of poplar wood and wood from garden pruning. The wooden raw material is chipped, screened, stored in silos and sent to a digester and heated with saturated steam and then transported into a refiner to convert wood into fiber bundles. The fibers are then mixed with adhesive and other additives and transferred to the fiber drying stage. Board production itself includes mat forming, prepress of mattresses, trimming and a continuous hot-press for board shaping.

In the board finishing subsystem, the boards are cut to standard size and cooled, the boards are kept under constant climatic conditions, sanded, graded and stored for supply to the market.

2.3. Production of bagasse-based MDF

The system boundaries for bagasse-based MDF production are shown in Fig. 3. Sugarcane residue (bagasse) is an annual agricultural plant residue and is one of the by-products from sugarcane production. Economic allocation was applied to split the GHG emissions between bagasse and other sugarcane by products. Although about 32% of the sugarcane weight is converted to bagasse, only 2.2% of the GHG emissions from growing and processing sugarcane were allocated to bagasse due to its relatively low economic value. Sugarcane (*Saccharum* spp.) is cultivated in two types of cultivation in Iran entitled Ratoon and Plant. The bagasse-based MDF factory with an annual production volume of 132,000 m^3 is located in the state Khuzestan in south-west Iran.

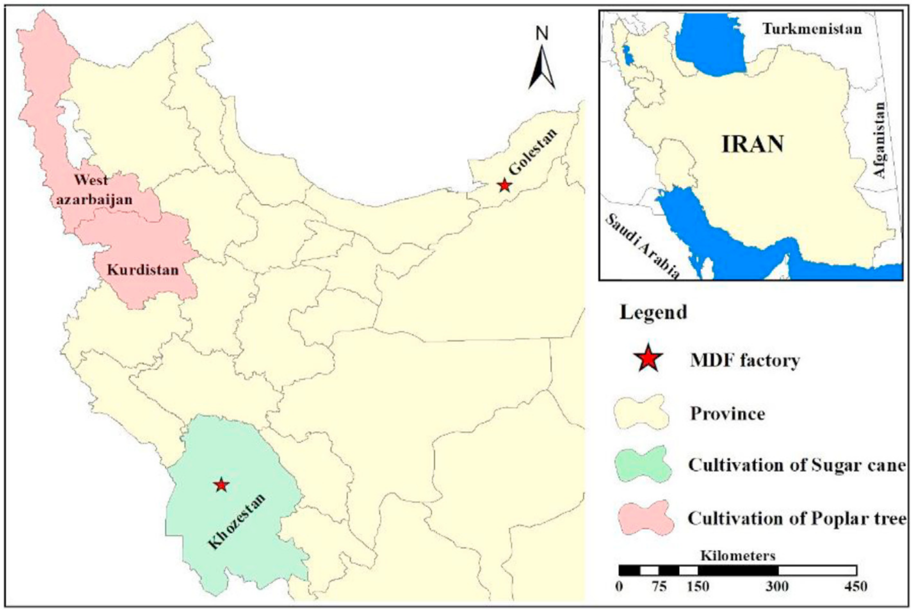

Fig. 1. Locations of the Surveyed MDF mills and biomass producer states.

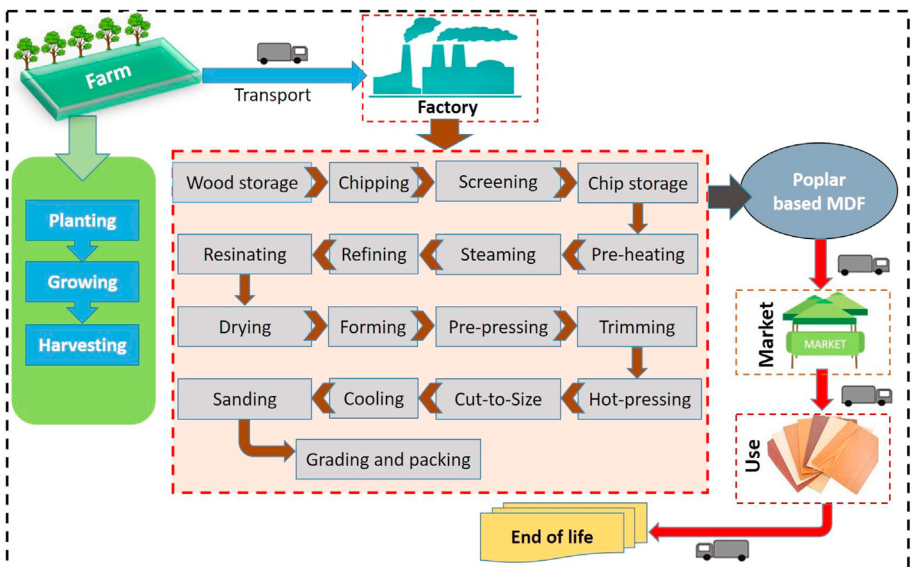

Fig. 2. System boundary (cradle-to-grave) of Poplar-based MDF production.

Fiber preparation starts with the preparation of lignocellulosic raw material (bagasse) for this factory. The average lignocellulosic raw material is depithed, stored, cleaned in wet conditions, dewatered and then transported into a refiner to be converted into fiber bundles. The bagasse fibers are then mixed with adhesive and other additives (properties of used urea-formaldehyde (UF) resin in factories are given in Table S1A of the supplementary information), after that the fibers were dried in fiber dryers. Board production contains mat forming, prepress of mattresses, trimming and a continuous hot-press for board shaping. In the board finishing subsystem the boards are cut to standard size and cooled, the boards are kept in constant climatic conditions, sanded, graded and stored for supply to the market.

2.4. Distribution, use and transportation to waste dumps and end of life

Foreground data was collected from the MDF mills managers and the drivers of the trucks about the transport distance for MDF distribution into sales center, delivery to consumers and used MDF transportation to waste dumps. GHG emissions resulting from the installation and use of the MDF were considered out of scope, apart from the biogenic carbon storage effect calculated over a time period of 40 years. The used MDF was transported by trucks with a payload of 10 t that consumed 40 L of diesel per 100 km distance. Raw material was usually transported by different trucks with a payload of 15 t and 24 ton and 2 ton vans. Each transportation section emission, was calculated using information related to transporter vehicles and transportation distances (see Table 1 for an overview of transport types and distances). The main reason for the longer distance in bagasse-based MDF distribution is that the sales centers of bagasse-based MDF are located in Tehran which is far from the factory.

Carbon storage periods of 10, 20, 30, 40 50 and 60 years are taken into account. Note that the function of the board changes slightly, the economic lifetime ranges from 10 to 60 years and the boards are not necessarily used in construction during the entire period because they

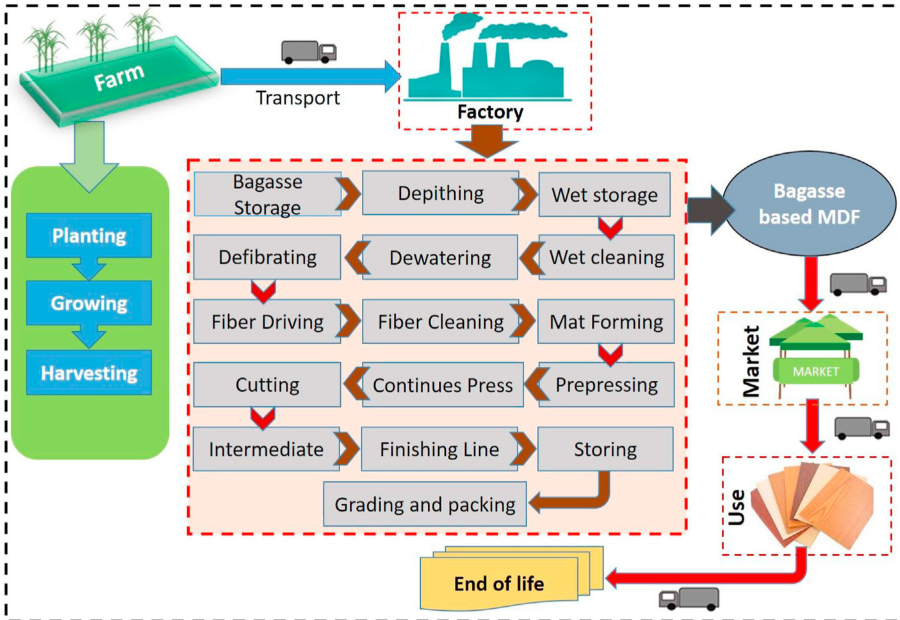

Fig. 3. System boundary (cradle-to-grave) of Bagasse-based MDF production.

may be repurposed after their initial use in construction. We made the simplifying assumption that any emissions related to the repurposing or use of the material are negligible and the only difference between the scenarios is the extended storage period. Data for the treatment of wastewater generated during the production of the panels were obtained from the Ecoinvent 3.6 database, as implemented in Simapro version 9.11 (Wernet et al., 2016). Biogenic emissions from burning the used panels at the end of life are already included in the used biogenic GWP factors. Emissions from burning the resin in the MDF panels are calculated based on the carbon content of the resin (see Table S10).

2.5. Global warming potentials

GHG footprints were calculated based on Global Warming Potentials without climate feedbacks for a 100 year time horizon (GWP_{100}) taken from IPCC, 2013. For biogenic carbon stored in the MDF, negative biogenic GWP factors were taken from Guest et al. (2013a), accounting for the rotation time of the crops and the time the MDF is stored in the economy. The biogenic GWP integrates the biogenic carbon dioxide (CO_2) fluxes with the global carbon cycle and the storage period of harvested biomass in the economy. The shorter the rotation time of the biomass feedstock and the longer the carbon storage in the economy, the higher the carbon storage benefits and the lower the biogenic GWP. Biogenic GWPs for 1 (sugarcane) and 12 year (poplar) rotation times and storage periods of 10, 20, 30, 40, 50 and 60 years are shown in Table 2. Because no GWP_{bio} factors were provided by Guest et al. (2013a) for a rotation period of 12 years, we used a weighted average of the factors for 10 and 20 year rotation periods.

2.6. Greenhouse gas footprints

The total GHG (GHG_{tot}) cradle-to-grave footprint for 1 m^3 of MDF was calculated via equation (1).

$$GHGtot_{i,s} = \sum_j LCI_{i,j} \times GHG_{i,j} + (MassMDF_i - Biomass_i) \times GHGwaste_i + GWPbio_{i,s} \times cc_i \times \frac{44}{12} \times Biomass_i \quad (1)$$

Where i represents the biomass source (bagasse-plant, bagasse-ratoon or poplar), s storage period of the carbon (no storge or 10, 20, 30, 40, 50, 60 years), LCI_j represents a life cycle input j (i.e. the amount of a certain process that is needed per m^3 of MDF) with its corresponding *GHG* emissions in kg CO_2-eq per unit of input j, *MassMDF* is the mass of 1 m^3 of

Table 1
Transport types and distances included in this study.

Transport type	Vehicle type (poplar-based MDF)	Average distance (poplar-based MDF)	Vehicle type (bagasse-based MDF)	Average distance (bagasse-based MDF)
UF-resin	Truck - 24 ton	600 km	Truck - 24 ton	570 km
Ammonium chloride and paraffin	Truck - 15 ton	1000 km	Truck - 24 ton	730 km
Main feedstock	Truck - 15 ton	1000 km	Conveyor belt	On-site
Pruning residues	Transport van	50 km	-	-
Factory-to-market transport	Truck - 10 ton	60 km	Truck - 24 ton	600 km
Market-to-consumption place	Truck - 10 ton	5 km	Truck - 24 ton	5 km
Consumption place-to-waste dump	Truck - 10 ton	10 km	Truck - 24 ton	10 km

Table 2
The biogenic 100 year time horizon Global Warming Potential (GWP_{bio}) used for bagasse-based MDF and poplar-based Medium Density Fiberboard (MDF) for storage periods from 10 to 60 years
(The rotation times of sugarcane and poplar wood are 1 years and 12 years respectively).

Carbon storage period (y)	GWP Bagasse (1 y rotation)	GWP_{bio} Poplar (12 y rotation)
10	−0.07	−0.03
20	−0.15	−0.11
30	−0.23	−0.19
40	−0.32	−0.27
50	−0.40	−0.36
60	−0.50	−0.45

MDF, *GHGwaste* are the greenhouse gas emissions for waste treatment of the Urea-Formaldehyde resin in the MDF board, *GWPbio* is the biogenic GWP (from Table 2), *cc* is the carbon content of the biomass, 44/12 is the ratio of the molecular weight of CO_2 and C and *biomass* is the mass of the biogenic material per m^3 of MDF.

Inputs related to biomass production, MDF factories and gate-to-grave transportation are presented in Table 3, while additional details are reported in Tables S2–S9 of the Electronic Supporting information. All calculations were performed using Microsoft Excel.

3. Results and discussion

3.1. Life cycle GHG footprint of MDF

The cradle-to-grave life cycle GHG emissions of using 1 m^3 poplar-based MDF and bagasse-based MDF as construction material are shown in Fig. 4. Cradle-to-grave GHG emissions per m^3, excluding the biogenic carbon storage, are 679 kg CO_2-eq/m^3 for poplar-based MDF and 849 kg CO_2-eq/m^3 for bagasse-based MDF. The majority of these emissions occur during the production of the MDF (491 kg CO_2-eq/m^3 and 653 kg CO_2-eq/m^3 for poplar and bagasse-based MDF respectively) with the fiber preparation stage being the most emission intensive step in the board creation process (391 kg CO_2-eq/m^3 and 525 kg CO_2-eq/m^3 for poplar and bagasse-based MDF respectively). Electricity and UF resin consumption were the main contributors in bagasse-based MDF and poplar-based MDF factories respectively. Raw material transport also has a relatively large contribution (108 kg CO_2-eq/m^3) for poplar-based MDF, caused by the long transport distance from the poplar plantations in northwestern Iran to the MDF factory in the northeastern part of the country. For bagasse-based MDF the transport for the distribution, use and waste disposal is relatively important (85 kg CO_2-eq/m^3), because the MDF factory in the southwestern part of Iran is far (600 km) from the sales centers in the province of Tehran. The contribution of the biomass production phase itself is limited, GHG emissions for poplar wood production (7 kg CO_2-eq/m^3 MDF) and bagasse production (5 kg CO_2-eq/m^3 MDF) (the average of plants method and ratoon method bagasse). For both the transport and the plantation phases the majority of the emissions is caused by burning diesel. See Table S10 for emissions from resin incineration.

The effect of the carbon storage during the 40 years of use in construction is −200 kg CO_2-eq/m^3 for poplar-based MDF and −356 kg CO_2-eq/m^3 for bagasse-based MDF (Fig. 4). This results in life cycle GHG emissions of 478 kg CO_2-eq/m^3 for poplar-based MDF and 493 kg CO_2-eq/m^3 for bagasse-based MDF. The effect of other carbon storage times (10, 20, 30, 40 50 and 60 years) is displayed in Fig. 5. In the most optimistic case (i.e. with all biomass stored for a period of 60 years) life

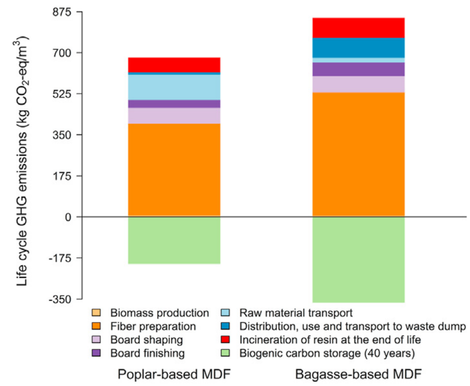

Fig. 4. Life cycle GHG emissions (kg CO_2-eq/m^3) of poplar- and bagasse-based MDF per life cycle stage.

Table 3
Energy and material requirements for 1 m^3 of MDF.

Inputs	Inventory						
	Poplar wood production	Bagasse production (Ratoon)[a] (1.44E+03 kg)	Bagasse production (Plant)[a] (1.44E+03 kg)	Transport and Poplar- based MDF Production	Transport Bagasse- based MDF Production	Distribution, use and transport to waste dumps for Poplar- based MDF	Distribution, use and transport to waste dumps for Bagasse- based MDF Production
Electricity (kWh)		–	–	2.00E+02	4.31E+02		
Natural Gas (m^3)		–	–	1.00E+02	5.00E+01		
Dried Urea formaldehyde resin(kg)	–	–	–	6.80E+01	9.30E+01		
Gasoline (l)	6.80E-01	2.90E-01	2.20E-01	7.70E-01	–		
Diesel (l)	3.70E-01	3.26E+00	7.54E+00	2.26E+01	4.13E+00	2.12E+00	1.78E+01
Poplar (moisture: 70%) (kg)	–	–	–	7.08E+02	–		
Waste wood from garden tree pruning (moisture: 70%) (kg)	–	–	–	4.27E+02			
Raw Bagasse (moisture: 60%) (kg)	–	–	–	–	9.81E+02		
NH_4Cl (kg)	–	–	–	1.78E+00	1.78E+00		
Paraffin wax (kg)	–	–	–	–	1.11E+01		
Diazinon (kg)	6.10E-04	–	–	–	–		
Urea fertilizer (46% N) (Kg)	4.60E-01	5.75E+00	4.31E+00	–	–		
Cow manure (kg)	7.00E-02	–	–	–	–		
Agricultural machineries (h)	1.10E-02	4.00E-02	1.90E-01	–	–		
Herbicides (kg)		7.30E-01	1.60E-01				
Phosphate fertilizer (as P_2O_5) (kg)		3.30E+00	2.44E+00				
Harvester (h)		1.60E-02	1.80E-02				
Waste water from MDF production (m^3)				1.00E+00	4.00E+00		

[a] Columns 2 and 3 are related to sugarcane production inputs for the required amount of bagasse for 1 m^3 bagasse-based MDF production, economic allocation was applied to the emissions resulting from these inputs.

cycle GHG emissions decrease to 345 kg CO_2-eq/m^3 for poplar-based MDF and 292 kg CO_2-eq/m^3 for bagasse-based MDF. For bagasse-based MDF the benefit of biogenic carbon storage is larger, because the rotation time of bagasse is shorter than that of poplar. The amount of biogenic carbon stored in poplar-based MDF is also slightly lower, because the biogenic carbon stemming from garden prunings and waste is not included, since we cannot be sure about the rotation time for these sources (see also Table S11).

3.2. Comparison with other studies

Comparing our results with the findings from other studies, it appears that the cradle-to-gate, GHG emissions of 1 m^3 poplar and bagasse-based MDF, excluding biogenic carbon storage and waste incineration, are equal or higher compared to other cradle-to-gate studies (Fig. 6), more details about the other studies can be found in Table S12. As none of the studies included biogenic carbon storage by accounting for rotation time and storage period, we added these carbon benefits ourselves to the previous studies in Fig. 6. The biogenic carbon storage in previous studies was estimated on the basis of average wooden species rotation period that were used as a raw materials in MDF boards and with a storage period of 40 years, following Guest et al. (2013a). Carbon storage values in literature are generally lower than the values in this study because of the short rotation periods for growing sugarcane (1 year) and poplar trees (12 years) compared to other softwood and hardwood species which are in the order of 10–90 years.

3.3. Improvement options and uncertainties

By taking into account biogenic carbon storage periods up to 60 years, the footprint of MDF was reduced from 680 kg CO_2-eq/m^3 to 347 kg CO_2-eq/m^3 for poplar-based MDF and from 850 to 293 kg CO_2-eq/m^3 for bagasse-based MDF. With long storage periods, MDF made from the annual crop residue bagasse outperforms MDF from poplar wood. In Iran around 688,000 tons of bagasse is produced annually (Mohammadi et al., 2020). This would be sufficient for 478,000 m^3 of MDF, about one-fifth of the total MDF consumption in Iran. The annual production of sugarcane bagasse globally is 493 million metric tons (Khattab and Watanabe, 2019), this is enough to cover the annual MDF production more than 3 times.

The footprints of both bagasse-based and poplar-based MDF can be further reduced by implementing a number of improvement options in the life cycle of MDF. During biomass production, diesel fuel consumption may be reduced by modifying agricultural operations, primarily by switching to more efficient modern agriculture machineries. To reduce life cycle GHG emissions of poplar-based MDF, diesel consumption can be reduced by shortening transport distances. For this purpose it is better that poplar wood is provided from Northern provinces in Iran, such as Mazandaran, Giluan and Golestan.

During MDF production, the GHG emissions of the wood fiber production subsystem can be improved by using renewable energy sources in the refiner, dryer fans and boilers (Skinner et al., 2016). For instance, electricity and thermal energy generation based on lignocellulosic waste from MDF production, such as oversized and undersized wood chips, sand dust and waste from board edge trimming, should be further stimulated (Wilson, 2010; Kouchaki-Penchah et al., 2016; Rivela et al., 2016; Silva et al., 2015).

There are also options to decrease urea formaldehyde consumption in MDF production, such as adding filler to the resin used in MDF manufacturing. The application of minerals, for example calcium carbonate, can replace cellulose fiber and reduce the percentage of resin consumption and manufacturing costs (Ozyhar et al., 2020). Adding filler-extender, such as oxidized starch to UF resin, can also reduce the total weight of used resin (Gadhave et al., 2017). Isocyanate is an alternative resin that could be used to improve the properties of agricultural waste-based panels (such as bagasse-based MDF) but its high cost is a limiting factor for industrial wide consumption, especially in developing countries such as Iran (Hafezi et al., 2016). Lignin and tannin are bio-based resins that, in combination with amino plastic or phenolic resins, can be used in MDF panel production but their products are not suitable for exterior usage (González-García et al., 2011).

Lastly, increasing the economic life time of MDF can reduce final GHG footprint in the consumption phase. Water permeability is one of the factors influencing fungal decay and therefore is a main determinant of the service lifetime of MDF panels (Kutnik et al., 2014). Application of substances to increase moisture and fire resistance has increased in recent years (Sandberg, 2016). One of the best methods for enhancing the durability and appearance of wood-based products such as MDF is to apply different types of coating such as polyurethane or cellulosic paint. Applying this solution improves the performance of the panels and increases the service life and characteristics (Landry et al., 2013; Erdinler et al., 2019). Polyurethane coatings can increase the MDF service life in places with limited moisture content. Heat-treated panels can be used in more damp conditions including ceilings, baths or kitchens due to high dimensional stability (Ates et al., 2017). Laminated MDF by wooden veneer and epoxy resin also enhance the durability of MDF panels

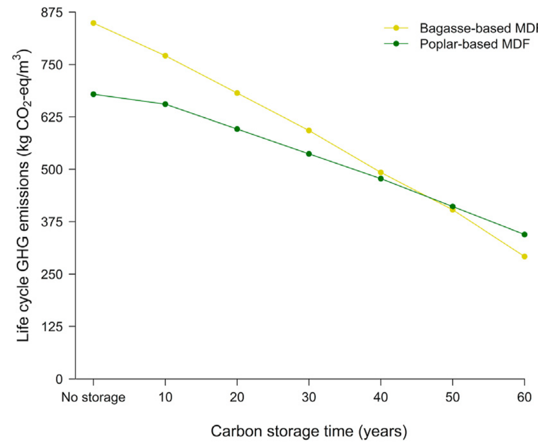

Fig. 5. Life cycle (cradle-to-grave) GHG emissions (kg CO_2-eq/m^3) for poplar- and bagasse-based MDF without biogenic carbon storage and with carbon storage times ranging from 10 to 60 years.

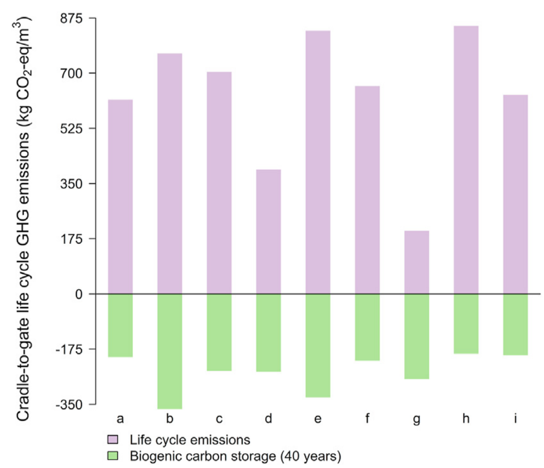

Fig. 6. Comparison with other fiberboard crade-to-gate life cycle GHG footprints (a. Poplar based MDF (this study), b. Bagasse based MDF (this study), c. Wilson, 2010, d. Athena Sustainable Materials Institute, 2013, e. Kouchaki-Penchah et al., 2016, f. Puettmann et al., 2016, g. Piekarski et al., 2017, h. Nakano et al., 2018 and i. Puettmann et al., 2013). Note that differences between studies shown here can partly be attributed to the fact that standards for fiberboards differ from country to country.

(Cahyono et al., 2020). An interesting avenue for further research is to compare the climate benefits of long-term carbon storage in bagasse-based MDF panels to other practices. Climate mitigation benefits have been shown for a variety of different bagasse uses, including bioelectricity, biofuels, biochar and fiber utilization in cement mixtures (e.g. Moreira et al., 2016; Kameyama et al., 2010; Micheal and Moussa, 2021). Because of the widely different functional units and counterfactuals employed in such studies, direct comparison of these mitigation potentials is not possible. To determine the optimal use of bagasse as source material, a comparison should be done on the basis of a common functional unit, for example starting with a specific amount of available bagasse, and with harmonization of the utilized counterfactuals (Hanssen and Huijbregts, 2019).

Here it should be noted however that temporary biogenic carbon storage does not in fact reduce the emissions, but rather delays them to a later point in time. The amount of credit that should be given to biogenic carbon storage is therefore also dependent on the chosen time frame and differs per methodology (Brandão et al., 2013). We view the storage of biomaterials in the economy as a carbon sink that can lower atmospheric CO_2 concentrations compared to a situation in which biomass would be burned right after the harvest. The longer this economic storage, the bigger this sink becomes, the biogenic carbon storage factors as derived by Guest et al. (2013a) match this vision. It should, however, be noted that in our study delayed fossil emissions (for example emissions from transport at the end of life) are not discounted, which can be seen as inconsistent. In order to adequately take this into account a fully dynamic LCA would have to be performed (Levasseur et al., 2010). We decided against such an approach, the overwhelming majority of fossil emissions occur in year 1 and therefore the limited benefit of this approach would not outweigh the added complexity in our case.

In this study the Ecoinvent 3.6 database was used to calculate GHG footprints. For some inputs, there wasn't any specific data for Iran and we used global averages, we have limited this as much as possible by collecting foreground data on-site as much as possible. When comparing our results to those of prior studies the exact name of wooden species were sometimes not given and calculations were based on averages, this may have influenced the comparison if the actual rotation time of the crop used in the study is much longer or shorter than the value we used.

4. Conclusions

Our study quantified the life cycle GHG footprint of 1 m^3 poplar-based MDF and bagasse-based MDF in Iran, including biogenic carbon storage. We found that poplar-based MDF has a GHG footprint of 345–655 kg CO_2-eq/m^3 and bagasse-based MDF of 292–771 kg CO_2-eq/m^3, depending on the carbon storage period. Without considering biogenic carbon storage, the GHG footprints of MDF are substantially higher, i.e. 679 kg CO_2-eq/m^3 for poplar-based MDF and 849 kg CO_2-eq/m^3 for bagasse-based MDF. Our findings imply that biogenic carbon storage needs to be appropriately included in the GHG life cycle calculations of biobased products, including MDF. While biogenic carbon storage has a larger effect on the life cycle GHG emisions for bagasse-based MDF compared to poplar-based MDF, this was not enough to compensate for the larger life cycle emissions when MDF is used for 40 years or less. Compared to MDF from poplar, the GHG footprint of MDF can be reduced by using annual crops such as sugarcane, but only if the economic life time can also be increased simultaneously. Other options to lower the footprints are using waste wood as renewable energy source and reducing formaldehyde use.

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.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.cesys.2021.100066.

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