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Conceptual 'Cradle to Gate' analysis of GHG emissions from wood, agricultural plant and synthetic fibres

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Abstract. Industrialization and fossil resource use has brought unprecedented anthropogenic carbon dioxide emissions. Use of synthetic fibre materials and unsustainable plant cultivation practices contribute to greenhouse gas emissions. The global market share of polyester fibre (synthetic fibre made from fossil resources) exceeded the share of cotton fibre (natural fibre) for the first time in 2000 and since then polyester has remained the most popular fibre. The demand for textiles keeps increasing. In Northern Europe locally made fibres from wood, hemp and flax could substitute fossil based fibres decreasing the global GHG emissions and helping local economies to prosper. Multi-criteria analysis method TOPSIS was used to carry out a conceptual research evaluating GHG emissions from wood, agricultural plant and synthetic fibre acquisition under two scenarios: fossil fuels are used as energy sources & industrial fertilizers are used; and renewable energy sources are used & industrial fertilizers are not used. Results show that wood and plant fibres have smaller GHG emissions than synthetic fibres in both scenarios. Factors affecting emission performance are analysed.

Key words: fibre, wood fibre, hemp fibre, flax fibre, synthetic fibre, carbon dioxide, multi-criteria analysis, TOPSIS.

INTRODUCTION

The data collected by Vlachogianni & Valavanidis (2013), International Energy Agency (2017) and British Petroleum (2017) reveal ever increasing reliance on fossil resources. Recently the only dip in the fossil resource consumption happened between 2008 and 2009, and was caused by the global financial crisis. Industrialization, urbanization, transportation, deforestation and energy production are driving the increase in the atmosphere's CO_2 concentration (Kumar et al., 2018). Since the late 19th century the CO_2 concentration has increased by approximately 50% from around 270 ppm to above 400 ppm (National Aeronautics and Space Administration, 2018). Recent anthropogenic rises in CO_2 levels have been more rapid than ever before the industrialization. The world annual average temperature rose by approximately a degree Celsius since the beginning of 20^{th} Century.

Trackable amount of CO_2 emissions can be avoided by substituting products made from fossil resources by products made from sustainably acquired biomass – CO_2 emissions during the production process have to be smaller than the avoided CO_2

emissions (Kalnbalkite et al., 2017). Substitution of fossil source based products with products made from biomass is a step to be taken to mitigate emissions. Due to the significant forest covered areas Poland, Lithuania, Latvia, Estonia and other Northern European countries could find the end of fossil era opportune.

Nearly everyone around the globe is a customer of the global textile industry. The global market share of polyester fibre exceeded the share of cotton fibre for the first time in year of 2000 and this trend has continued (Palamutcu, 2017). Fibre demand is increasing and it reached 95.6 million tons in 2015. The increase of the world fibre market consumption was up to 99 million tons in 2016 and fossil source based synthetic fibres had the biggest share with 62.7%, cotton fibres took 24.3%, wood-based cellulose fibres around 6.6%, cellulosic and protein-based other fibres had 5.3% and wool around 1.1% (Lenzing Annual Report, 2016). Hemp, flax and wood fibres are advantageous and have suitable qualities to be cultivated in Northern Europe and cultivation is associated with low water, fertilizer and pesticide requirements (Zommere et al., 2013). The current global market share of hemp, linen and wood fibre textiles is multiple times smaller than the share of cotton textiles, however it is growing but growing demand for environmental friendly, skin friendly and bio-degradable textiles will be the key factor, expected to drive the market by 2020 (Palamutcu, 2017).

Cellulose content in hemp and flax is around 70%. Cellulose in wood constitute between 40-50%. Because cellulose extraction from wood involves a significant thermochemical phase therefore wood fibres are categorized as naturally derived synthetic fibres. Current technology advancements allow wood fibres to be produced via advanced 'closed loop' process minimizing impact on the environment. For example wood fibre lyocell which is a brand of rayon fibre production uses an amine oxide (a non-toxic solvent) which is continually recycled during the production process – 99% of solvent used in the cellulose extraction can be recovered (Shen & Patel, 2010).

Stockholm Environment Institute published research summarizing that use of fossil resources as a material for fibre production can have smaller impact on the environment than agricultural cultivation because agricultural cultivation involves use of pesticides and insecticides causing toxicological effect on the environment (Cherrett et al., 2005). The production and use of nitrogen containing fertilizers (such as HNO_3) generate considerable amounts of greenhouse gas (GHG) emissions and the global warming potential of N_2O for 100 year period is 310 times greater than CO_2. Soil emissions of N_2O were assumed to be linearly related to N fertiliser rate with 0.0157 kg N_2O per kg N from direct emissions; plus 0.0036 kg N_2O per kg N indirect emissions from leaching and 0.0015 kg N_2O per kg N from volatilisation, giving a total of 0.0208 kg N_2O per kg N, or 6.16 kg CO_2 equivalent per kg N; the average GHG emissions associated with the manufacture, packaging and transport of ammonium nitrate fertiliser were estimated to be 7.11 kg CO_2 equivalent per kg N (Kindred et al., 2008). Land cover change assuciated with deforestation directly affects the surface-atmosphere interactions changing moisture and further influence the atmospheric thermodynamic characteristics (Li et al., 2013).

Cotton crop cultivation and fibre production requires between 11,000 MJ and 32,000 MJ per ton and polyester 'cradle to gate' energy requirements are between 104,000 MJ and 126,000 MJ per ton, however synthetic fibre polyester manufacturing stages require very little if any water (Palamutcu, 2017).

Terinte et al. (2014) carried out ‘cradle to gate’ life cycle analysis (LCA) of undyed modal (wood cellulose fibre) – they found equivalent emissions to be 2.05 kg CO_2 emissions per kg of modal fabric. According to Walser et al. (2011) ‘cradle to gate’ analysis the equivalent emissions of 1 kg polyester t-shirts are 19.6 kg CO_2. According to Roos et al. (2015) ‘cradle to gate’ analysis of 1 kg polyster dress are 21 kg CO_2. Thomas et al. (2012) ‘cradle to gate’ analysis of different garments fibres results show that the average equivalent emissions of 1 kg flax /linen garments are 15 kg CO_2, 1 kg polysester garments are 21.3 kg CO_2 and average equivalent emissions of 1 kg cotton garments are 27.7 kg CO_2. Van der Velden et al. (2014) estimated the equivalent CO_2 emissions of 1 kg cotton fibre (cradle to gate) to be between 9 and 22,5 kg CO_2. Shen & Patel (2011) ’cradle to gate’ analysis found that 1 kg lyocell equivalent emissions were 1.5–2.5 kg CO_2, pointing that the required land area for wood to produce lyocell can be 4 times smaller than the land required to produce equal amount of cotton fibre (Shen & Patel, 2010). Methodology details (handling of biogenic CO_2 emissions and soil carbon changes) are rarely clearly stated in the studied carbon footprint calculations (Roos et al., 2015).

Different locations require different amounts of fertilizers, insecticides and energy inputs. Similarly the available energy sources, production technologies, staff work-culture and logistics change from one location to another. Although there are differences in emission results for cotton, hemp and linen, it can assumed that the average CO_2 emissions from these fibres are similar and depend on the plant cultivation practices, fibre production technologies and energy sources. Use of industrial fertilizers and fossil resources are economically viable because the external costs such as GHG emissions are not internalized. GHG emissions are externalities and represent the biggest market failure the world has seen (Tsigaris & Wood, 2016).

This paper compares two scenarios of GHG emissions associated with fibre material acquisition for selected fibres – wood fibres, agricultural plant fibres and synthetic fibres. Raw material cultivation / extraction, base material production the material GHG emissions are analysed. The first scenario studies current industrial agriculture practices and the second scenario studies sustainable agricultural practices.

METHODOLOGY

This research evaluates GHG emissions of different fibres using multi criteria analysis (MCA) TOPSIS (*Technique for Order Preference by Similarity to Ideal Solution*) (Jahan et al., 2016). TOPSIS is performed by placing available alternatives (in this case fibre materials) and identified influencing factors (GHG emission sources of fibre acquisition process) in a matrix, identifying the relevant factors for a particular fibre and carrying out normalization calculations according to TOPSIS methodology. Upon completion of the calculations the most desirable alternative should have the shortest geometric distance from the ideal solution - whichever fibre acquisition is closer to 0 anthropogenic emissions is the most desirable alternative. The acquisition of the selected fibres were explored under two different scenarios:

1) fossil resources are used to power the production processes and industrially produced fertilizers are used;

2) renewable resources are used to power the production processes and agricultural practices are sustainable.

In both scenarios the alternative that is closest to the ideal situation is when the result is closest to 0 – no anthropogenic GHG emissions.

Literature review identified factors contributing to GHG emissions of fibre acquisition for three selected fibres: a derived synthetic fibre from wood, agricultural plant fibre (hemp /flax) and synthetic fibre polyester. Following possible GHG emission factors of fibre production were identified: use of industrial fertilizers; deforestation; extraction & fibre base material production; high energy intesity; and additional carbon introduction into atmosphere. The use of industrial fertilizers is mainly associated with agricultural plant fibre acquisition as trees do not have high soil nutrient requirements. Depending on the technologies agricultural plant cultivation as well as increased demand for wood fibres can be associated with deforestation. Extraction & base material production is associated with all three fibre acqusition. Possible CO_2 emissions from energy consumption to power processes is a significant factor – in the data matrix energy intesity represents the sum of average energy requirements of different production stages for each fibre which were found out in the literature review. The use of fossil sources generate additional CO_2 emissions and use of renewable energy sources is CO_2 neutral. The overall energy intesity still is an economic factor determining the choice of producing one good over another. Additional carbon introduction into the atmosphere is a factor showing whether the product is related with using the carbon already within biosphere or introducing carbon from the subterranean depths of earth into the biosphere which is not desirable considering the current the topicality of this paper.

A numerical weight was assigned to every factor (Table 1). The total sum of all assigned numerical weights is 1 – it can also be viewed as 100% however not all factors apply to each fibre. For example use of fertilisers is not related with acquisition of synthetic fibres. Weight of an individual factor is chosen relative to weights of other factors. The weights of factors were distributed accordingly: 0.15 is industrial fertilizer use, 0.15 is deforestation, 0.05 is extraction and & base material production (emissions from chemicals), 0.25 is energy intensity and 0.4 is additional CO_2 release into the atmosphere. Additional CO_2 release into the atmosphere was assigned the greatest numerical weight because the extraction of fossil resources add extra carbon to the carbon cycle eventually contributing towards increase in CO_2 emissions. If a fibre acquisition includes particular factor then in the matrix it is identified with '1', absence of factor is identified with '0'.

RESULTS AND DISCUSSION

The selected materials do not contain pure cellulose parts like cotton therefore extraction stage exists both for wood and agricultural plant fibres and here direct GHG emissions can be generated from energy source choice and indirect GHG emissions can come from the use of chemicals in extraction processes. The acquisition of fossil resources and base material production also involve direct GHG emissions that can be generated from energy source choice and indirect GHG emissions that can come from the use of chemicals in extraction processes. Literature review revealed significantly higher energy demand for wood and synthetic fibres in the thermochemical phases. The energy requirements for agricultural plants are lower because of the cellulose content in plants is higher and preparation for extraction is also less energy intensive. This study does not take into account the relatively long time that is needed for trees to grow.

The first alternative scenario explores GHG emissions from cultivation and production of the selected fibres using industrial fertilizers and fossil fuels. Table 1 shows the MCA TOPSIS data matrix. It was assumed that deforestation is caused by wood fibres, but not by agricultural fibre cultivation because the use of industrial fertilizers ensure greater yield per hectare.

Table 1. Multi criteria analysis matrix of GHG emissions from selected textiles. Scenario 1: fossil fuels and industrial fertilizers are used

	Stage of life cycle (factors)	Wood fibres	Agricultural plant fibres	Synthetic fibres	Attributed weight
1	Use of fertilisers	0	1	0	0.15
2	Deforestation	1	0	0	0.15
3	Extraction & base material production	1	1	1	0.05
4	High energy intesity	1	0	1	0.25
5	Additional Carbon introduction into biosphere	0	0	1	0.4
	Total TOPSIS analysis score	0.35	0.24	0.67	

Fig. 1 shows the results of the first scenario. The lowest GHG emissions results in this are from agricultural plant fibres resulting in 0.24 points. Fertilizer use is the most significant factor. The overall energy intensity in the agricultural plant fibre cultivation and production is low compared to other fibres. Wood fibres with 0.35 points do not need industrial fertilizers however the fibre production is energy intensive because the content of cellulose is smaller than in agricultural plant fibres, therefore wood fibres are the second best alternative. Synthetic fibres with 0.67 points are the least desirable alternative -they are made from fossil resources and the currently known production practices are energy intensive as well as the extraction and fibre base material production are associated with GHG emissions, however the use of fossil sources is not related with fertilizer use and deforestation. If the factor 'additional CO_2 release into atmosphere' would not be included then agricultural fibres would score 0.39 points, synthetic fibres would score 0.45 points and wood fibres would score 0.61 points.

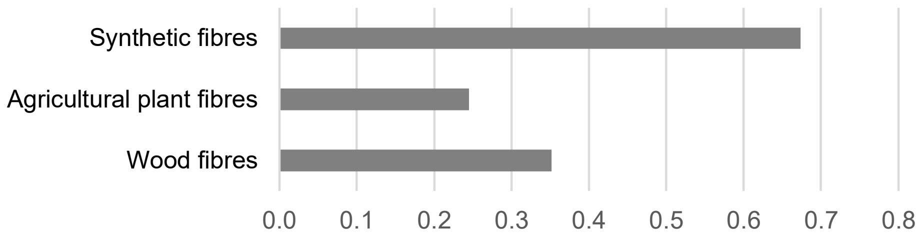

Figure 1. Multi-criteria analysis results of GHG emissions from selected textiles. Scenario 1: fossil fuels and industrial fertilizers are used.

If in the first scenario it is assumed that wood fibres do not cause deforestation then wood fibres wood be the most desirable scenario scoring 0.28 points and agricultural fibres would be the second best alternative with 0.33 points. And if it is assumed that both wood and agricultural fibres cause deforestation agricultural fibres would score 0.30 points and wood fibre would score 0.33 points.

The second scenario (Table 2) assumes that renewable energy sources are used and agricultural plant cultivation is done sustainably without using industrial fertilizers - not causing additional anthropogenic CO_2 emissions. It is known that sustainable agriculture is associated with lower yields therefore assumption was made that agricultural fibre cultivation will cause deforestation. CO_2 emissions can be generated also from extraction and base material production for all three types of fibre and also additional CO_2 will be released into the atmosphere by the use of fossil sources as raw material for synthetic fibre production.

Table 2. Multi criteria analysis matrix of GHG emissions potential from different textiles. Scenario 2: fossil fuels and industrial fertilizers are not used

	Stage of life cycle (factors)	Wood fibres	Agricultural plant fibres	Synthetic fibres	Attributed weight
1	Use of fertilisers	0	0	0	0.15
2	Deforestation	1	1	0	0.15
3	Extraction & base material production	1	1	1	0.05
4	High energy intesity	0	0	0	0.25
5	Additional Carbon introduction into biosphere	0	0	1	0.4
	Total TOPSIS analysis score	0.18	0.44	0.56	

Fig. 2 illustrates the results of the second scenario. The lowest GHG emissions results are from wood fibres resulting in 0.18 points. Wood fibres generate GHG emissions from deforestation and extraction & fibre base material production stages. Agricultural plant fibres are second best alternative with 0.44 points. The negative side-effect of sustainable fertilizer use in agricultural plant fibre cultivation could be deforestation due to increased land requirements. Synthetic fibres with 0.56 points are the least desirable alternative.

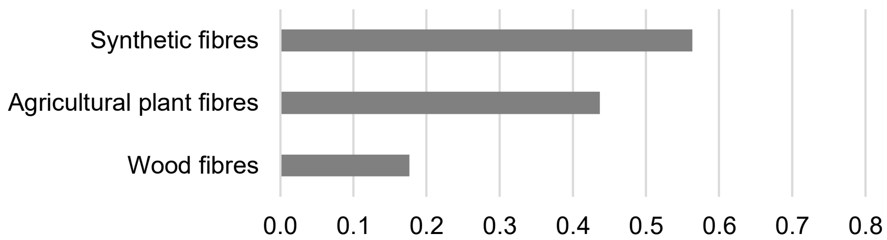

Figure 2. Multi-criteria analysis results of GHG emissions from selected textiles. Scenario 2: fossil fuels and industrial fertilizers are not used.

If the factor ‘additional CO_2 release into atmosphere would not be included’ then the production synthetic fibres would be the most desirable with only extraction and base material production causing GHG emissions and wood fibres would be in the second place.

CONCLUSIONS

Multi-criteria analysis TOPSIS based on the data from literature review was carried out to estimate 'cradle to gate' GHG emissions from selected fibre materials: wood fibres, agricultural plant fibres and synthetic fibres. Two scenarios were explored:

1) fossil resources are used to power the production processes and industrially produced fertilizers are used;

2) renewable resources are used to power the production processes and agricultural practices are sustainable.

The results show that in first scenario agricultural plant fibres have the smallest GHG emissions followed by wood fibres and synthetic fibres have the highest GHG emissions. The reason for agricultural plans to be more attractive in this case is related with the high energy demand of fibre extraction from wood sources. Both wood fibre and synthetic fibre production technologies are energy intensive. Under sustainable management, if only renewable energy sources are used wood based fibres would have the smallest GHG emissions. Industrial fertilizer use for agricultural plant cultivation increases GHG emissions, however ensures greater yields per hectare. Sustainable agriculture cultivation could mean increased demand for land and lead to deforestation. It is important to note that proper technology of fiber acquisition can reduce or at least optimize water impact.

This research is conceptual therefore indicative and should be taken as a rough base for making real life decisions. Further researches about possibilities of locally producing sustainable fibres should be carried out.

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