Analysis of raw material availability for the production of bio-based composites in South Africa

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ABSTRACT

Current research on building materials manufactured with renewable and secondary resources is gaining attention. This is due to the fact that the use of such resources can possibly improve environmental aspects related to the building industry (Kooduvalli et al., 2019; Sullens et al., 2015). The demand for building materials has increased, especially in countries that experience rapid population growth and intensive expansion of urban areas. This development was observed in South Africa, where rapid population growth worsens the already existent lack of housing. Population growth and urbanization affects how and for which purpose local resources are demanded. In addition, these developments raise waste generation and demand assertive waste management techniques.

Motivated by the concern of resource scarcity and lack of housing in South Africa, this study assessed the local availability of renewable and secondary resources suitable for the manufacture of bio-based building materials. Different methodologies of material flow analysis were adopted to investigate each resource. This study observed that South Africa has plenty of renewable resources, especially lignocellulosic materials sourced from forests, clearing of invasive alien plants (IAP) and processing of agricultural crops. In 2018, at least 7.4 million metric tons of these materials were locally available, of which IAP accounted for 92 %. Regarding secondary resources, this study revealed considerable volumes of plastic, ash, and slag available in South Africa. At least 54 million metric tons of these secondary resources were available and could have been utilized for the manufacture of building materials in the country. Nevertheless, material flow analysis alone cannot develop a more sustainable building industry in South Africa and tackle the housing shortage. Among others, policy incentives and the development of better waste management techniques are essential to increase resource efficiency. The relevance of this study lies within the compiled information about resources availability and is therefore an important step to support a further development of bio-based building materials in South Africa.

ZUSAMMENFASSUNG

Die aktuelle Forschung zu Baumaterialien, die aus erneuerbaren und sekundären Ressourcen hergestellt werden, gewinnt an Aufmerksamkeit. Dies ist darauf zurückzuführen, daß die Verwendung solcher Ressourcen möglicherweise Umweltaspekte im Zusammenhang mit der Bauindustrie verbessern kann (Kooduvalli et al., 2019; Sullens et al., 2015). Die Nachfrage nach Baumaterialien hat zugenommen, insbesondere in Ländern, die ein schnelles Bevölkerungswachstum und eine zunehmende Expansion der städtischen Gebiete verzeichnen. Diese Entwicklung wurde in Südafrika beobachtet, wo das rasche Bevölkerungswachstum den bereits bestehenden Mangel an Wohnraum verschärft. Das Bevölkerungswachstum und die Verstädterung wirken sich darauf aus, wie und für welche Zwecke die lokalen Ressourcen benötigt werden. Darüber hinaus erhöhen diese Entwicklungen das Abfallaufkommen und verlangen nach durchsetzungsfähigen Abfall- und Recyclingtechniken.

Motiviert durch die Sorge um die Ressourcenknappheit und den Wohnungsmangel in Südafrika wurde in dieser Studie die lokale Verfügbarkeit von erneuerbaren und sekundären Ressourcen untersucht, die für die Herstellung von biobasierten Baumaterialien geeignet sind. Zur Untersuchung der einzelnen Ressourcen wurden verschiedene Methoden der Stoffstromanalyse angewandt. In dieser Studie wurde festgestellt, daß Südafrika über zahlreiche erneuerbare Ressourcen verfügt, insbesondere über lignozellulosehaltige Materialien, die aus Wäldern, der Rodung invasiver gebietsfremder Pflanzen (IGP) und der Verarbeitung von landwirtschaftlichen Erzeugnissen stammen. Im Jahr 2018 waren mindestens 7,4 Millionen Tonnen dieser Materialien lokal verfügbar, wovon 92 % auf IGP entfielen. Was die sekundären Ressourcen betrifft, so ergab die Studie, daß in Südafrika erhebliche Mengen an Kunststoffen, Asche und Schlacke verfügbar sind. Mindestens 54 Millionen Tonnen dieser Sekundärrohstoffe waren verfügbar und hätten für die Herstellung von Baumaterialien im Land genutzt werden können. Dennoch kann eine Stoffstromanalyse allein nicht ausreichen, um eine nachhaltigere Bauindustrie in Südafrika weiter zu entwickeln und den Wohnungsmangel zu beheben. Um die Ressourceneffizienz zu steigern, sind unter anderem politische Anreize und die Entwicklung besserer Abfallbewirtschaftungstechniken erforderlich. Die Relevanz dieser Studie liegt in den

gesammelten Informationen über die Ressourcenverfügbarkeit und ist daher ein wichtiger Schritt zur Unterstützung der weiteren Entwicklung biobasierter Baustoffe in Südafrika.

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ABBREVIATIONS

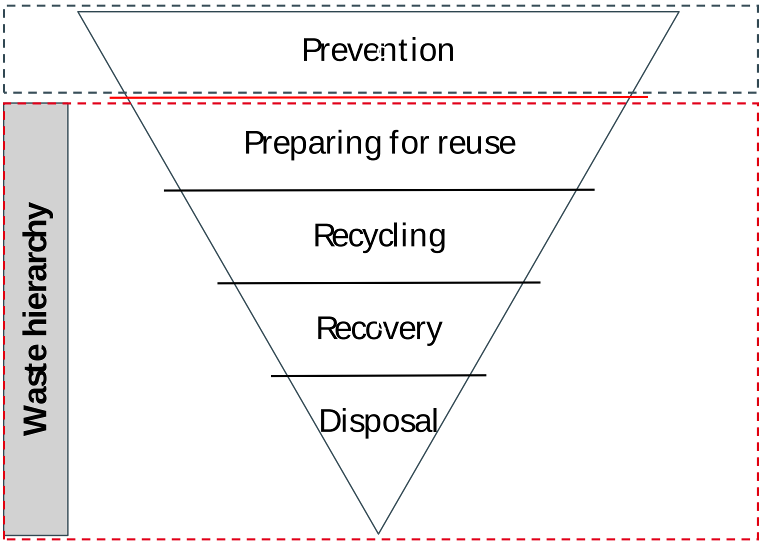
BBC	bio-based composite
BEA	Bio Energy Atlas for South Africa
BEFS	Bioenergy and Food Security rapid appraisal
CBE	circular bioeconomy
CE	circular economy
cm	centimeter
DAFF	Department of Agriculture, Forestry and Fisheries
DEA	Department of Environmental Affairs
DWAF	Department of Water Affairs and Forestry
FAO	Food and Agricultural Organization of United Nations
ha	hectare
IAP	invasive alien plants
IEA	International Energy Agency
kg	kilogram
LCM	lignocellulosic material
m^2	square meter
m^3	cubic meter
MFA	material flow analysis
mm	millimeter
mt	metric ton
NDP	National Development Plan
NWMS	National Waste Management Strategy
PAMSA	Paper Manufacturers Association of South Africa
RDP	Reconstruction and Development Programme
SAEON	South African Environmental Observation Network
SAGIS	South African Grain Information Service
SANBI	South African National Biodiversity Institute
SAPIA	Southern African Plant Invaders Atlas
SoWR	State of Waste Report
SSA	sub-Saharan Africa
Stats SA	Statistics South Africa
swe	solid wood equivalent
UNECE	United Nation Economic Commission for Europe
WPC	wood plastic composites
WPR	wood processing residues

1 INTRODUCTION

The manufacture of non-renewable building materials, based on concrete, metal and plastic demands huge quantities of energy and is responsible for high carbon emissions (Göswein et al., 2021), and is therefore considered harmful to the environment (Desing et al., 2021). In contrast, alternative building materials made with renewable and secondary resources not only consume less energy (Ben-Alon et al., 2019), but they also alleviate the pressure mounted on non-renewable and primary resources (Maraveas, 2020). An effective action toward alleviating resource scarcity and exploitation is reusing and recycling materials (European Commission, 2020). However, the precarious recycling structures in several countries create barriers to improving resource efficiency (DEA, 2018), for example by hindering the collection of such materials.

A major factor that impacts the demand for building materials is rapid population growth and the urbanization process. According to recent projections, the current world population may reach 9.7 billion inhabitants by 2050 and will be concentrated especially in the Global South (United Nations, 2019). These countries, for instance South Africa, are already experiencing a lack of housing for their current populations (Adegun & Adedeji, 2017). South Africa imported more renewable building materials in the form of wood-based products for construction in 2019 than it did in 2001 (DAFF, 2018; FAO, 2018a). However, these imports were not enough to supply renewable building materials for the country.

Aware that rapid population growth also increases waste generation, we now know that it is crucial to increase reuse and recycling rates in turn, and to improve overall resource efficiency in the Global South. This is an important step towards more circular economies in these regions. The circular economy concept aims at resource efficiency with a positive environmental impact in production processes (European Commission, 2020). An additional positive impact is feasible if building material production prioritizes the utilization of local resources (Gupta, 2017; Soneye et al., 2016), but preventing waste generation is the most important step towards more circular economies regardless. The waste hierarchy, presented in Figure 1, indicates the essential steps to avoid waste generation, of which the disposal of resources is the last acceptable step.



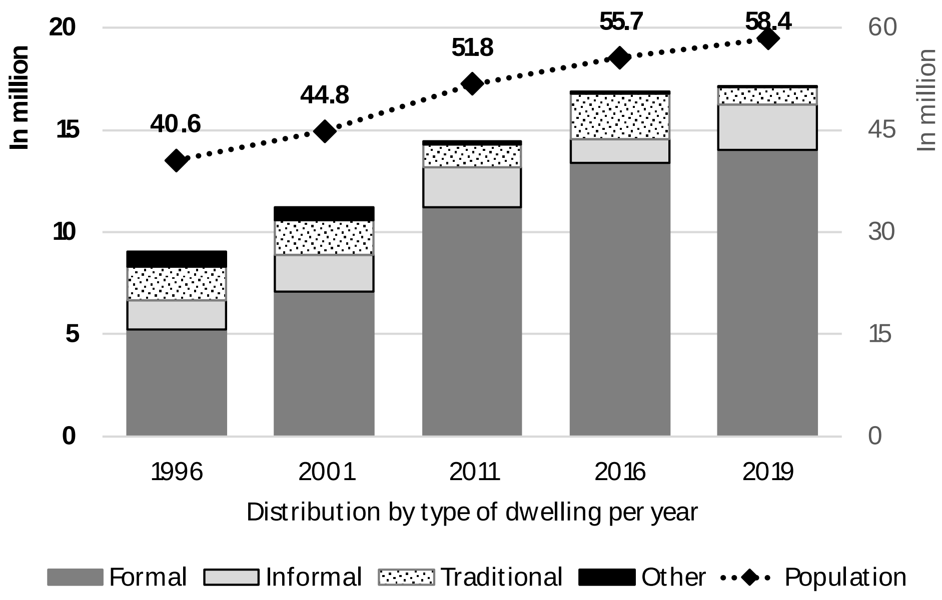
Source: Directive 2008/98/EC (Directive 2008/98/EC of the European Parliament and of the council of 19 November 2008 on waste and repealing certain, 2008)

Figure 1 – Waste hierarchy

The increasing demand for building materials is an inevitable trend in South Africa. In addition, the urbanization process demands a better waste management structure than what is currently available in this country (DEA, 2018). Is it possible to manufacture building materials made with renewable and secondary resources locally available in South Africa, and how can these resources be supplied? To answer these questions, an investigation on resource availability is necessary.

1.1 URBANIZATION IN SOUTH AFRICA

The Sub-Saharan Africa (SSA) region comprises 46 countries, with South Africa among them. The majority of SSA countries have experienced a rapid urbanization process and demographic trends indicating that, by 2030, the majority of population in these countries will live in urban areas (RSA, 2012). According to the national census periodically carried out in South Africa, from 1996 to 2019, the population grew by 1.6 % annually. In 2016, the census survey counted 55.7 million inhabitants, distributed across 16.9 million households. Figure 2 presents the evolution of population and number of household units in South Africa between 1996 and 2019.



Source: Department of Statistics South Africa (Stats SA, 2012, 2016, 2020)

Figure 2 – Evolution of population and household units by type of dwelling in South Africa

Households located in rural areas; labelled “Traditional” dwellings (Figure 2), registered a reduction from 1.6 million in 1996 to 875,000 in 2019 (Stats SA, 2016, 2020). The population’s moving from rural to urban areas has accelerated the urbanization process in South Africa. This growing urban population has also increased waste generation in specific regions of the country (DEA, 2018).

“Informal” dwellings, commonly called “shacks” or “shanties” (Figure 23 in the appendix), represented 12.7 % (2.2 million dwellings) of the total household units registered in 2019. From 2016 to 2019 alone, an additional one million dwellings were registered as informal in South Africa (Stats SA, 2020). “Formal” dwellings (14 million), in contrast, represent urban households, and at least four million of these units were subsidized through the Reconstruction and Development Programme (RDP). Concerns about the low quality of RDP houses are mentioned in official reports (Stats SA, 2020) and visible when visiting a RDP house (Figure 24 and Figure 25 in the appendix).

The number of household units has increased substantially in South Africa since 1996, but still at a much slower pace than the increase of the urban population. Urbanization pressure and unsettled recycling capacity impose barriers to the reuse and recycling resources for construction. Even with governmental support actions (DEA, 2012; RSA, 2012), recycling remains neglected in South Africa (Brosowski et al., 2016; Mwanza & Mbohwa, 2017), and the question remains as to whether the locally available resources are suitable to sustainably supply building materials.

The monitoring of resources can facilitate this sustainability across the building industry through the integration of information about the potential supply and uses of any type of resource. This is particularly important for the collective building industry of the Global South, where cheap construction materials are essential to combat the lack of affordable housing (Díaz-Ramírez et al., 2019; Malkawi et al., 2020; Rodier et al., 2019; Ye et al., 2018). However, the validity of these monitoring results depends on data reliability (Schwab et al., 2017): it must cover two main material flows, input (supply) and output (uses). This simple overview enables the building of a material flow analysis (MFA) for all types of resources. MFA has been widely applied to the monitoring of waste resources, especially to the disclosure of the share of recyclable materials (Allesch & Brunner, 2015; Eckelman & Chertow, 2009; Jacob et al., 2014; Laner et al., 2016; Vujic et al., 2010). Waste management in South Africa remains at an early stage. However, the last national census recorded useful information about waste generation and recycling rates there (Stats SA, 2012).

1.2 PROBLEMS AND OBJECTIVES

Rapid population grow and urbanization are contemporary developments that have significantly increased the need for building materials. The manufacture of building materials based on non-renewable resources is unsustainable and must adapt to more environmental-friendly alternatives. SSA countries like South Africa have suffered through a rapid urbanization process and have struggled to provide housing for their current populations and this will only intensify in the future. Urbanization process demands a better waste management structure than what is currently available in South Africa. However, is it possible to manufacture building materials made with renewable and secondary resources locally available there? What kinds of resources could sustainably supply building materials for the rapidly growing population of South Africa? To answer these questions, an investigation on resource availability is necessary. The stepwise construction of this study is listed as follows:

- The selection of two alternative building materials manufactured with renewable and secondary resources;
- Data collection on the availability of suitable raw materials for manufacturing said selected alternative building materials; and
- Resource monitoring via MFA for each of the available and suitable raw materials.

The estimated volumes of suitable raw materials support the design phase of prototypes of alternative building materials for South Africa. They also give evidence of which renewable and secondary resources are potentially raw materials for these purposes. The next section elaborates on the way in which the content of this study is structured.

1.3 STRUCTURE

This study encompasses five chapters. The first chapter, the Introduction, gives an overview of the regional context of South Africa and explains the issues related to population growth and urbanization pressures in this country. The second chapter, State of the art, begins with an analysis of two alternative building materials manufactured with renewable and secondary resources. The third chapter presents which raw materials are suitable for the manufacturing of the aforementioned building materials. Here the methods applied to investigate local availability of these suitable raw materials in South Africa are also presented. This chapter details all of the steps to perform material flow analyses of four different types of raw materials and estimate their local availability in South Africa. The fourth chapter entails the results and discussions of and on the material flow analyses calculations, presented in text, tables and figures to facilitate comprehension. Finally, the last chapter summarizes the key results and presents future research recommendations and other final remarks. Figure 3 shows the structure of chapters and their topics.

Content	
Chapter 1 Introduction	Urbanization in South Africa Problems and objectives Structure
Chapter 2 State of the art	Building materials based on renewable and secondary resources Monitoring renewable and secondary resources
Chapter 3 Materials and methods	Resources for alternative building materials in South Africa Monitoring resources via material flow analyses
Chapter 4 Results and discussions	Material flow analyses results Availability of local renewable and secondary resources
Chapter 5 Conclusions	Summary of findings Suggestions and recommendation Further research

Figure 3 – Structure of this study

2 STATE OF THE ART

2.1 BUILDING MATERIALS BASED ON RENEWABLE AND SECONDARY RESOURCES

The building materials made with renewable and secondary resources are usually called “sustainable”, “eco”, “green”, “bio” or “environmentally friendly” products (Suárez et al., 2021). Scientific research refers to building materials made with renewable resources as bio-based composites (BBC). Composites are understood as a blend of two or more materials to improve the performance of their original components (Arjmandi et al., 2017). In literature, a BBC is usually defined as a matrix and a dispersed phase in which renewable resources often represent the dispersed phase (Yousif, 2017). Natural fibers are the most utilized renewable resource for BBC manufacture. These fibers are based on cellulose, hemicellulose and lignin. Technically named lignocellulosic materials (LCM), these renewable resources have recently received attention of researchers. However, the availability of these LCM is impacted by other societal demands too. This is because they represent the fourth largest energy source globally, behind coal, oil and natural gas (Jawaid et al., 2017; Nasrullah et al., 2017). The monitoring of LCM typically utilized as energy source, such as firewood, is essential to revels the equilibrium between its material and energy uses.

The utilization of LCM is being extensively investigated to better understand its effect on BBC mechanical strengths (Bhaskar et al., 2012; Nourbakhsh & Ashori, 2010; Serra-Parareda et al., 2020), thermal and acoustic insulation properties (Asdrubali et al., 2015; Kroehong et al., 2018; Liu et al., 2017; Opoku et al., 2020; Rojas et al., 2019), and environmental performance (He et al., 2020; Rodier et al., 2019; Schwarzkopf & Burnard, 2016; Shanmugam et al., 2021; Suárez et al., 2021) and different types are being investigated for BBC manufacture. For instance, the African building industry has already recognized that secondary LCM, such as agricultural byproducts offer a possibility for substituting non-renewable resources (Adegun & Adedeji, 2017).

A recent review paper on bio-based building materials made with agricultural byproducts mentions that reutilizing this residue facilitates the improvement of waste management in rural areas (Maraveas, 2020). Additionally, the utilization of other LCM, such as wood, has been an object of study for BBC manufacture (Kamdem et al., 2004; Krause et al., 2018). However, the question of how much LCM of various types is available to supply BBC manufacture remains unanswered.

The manufacture of BBC and other alternative building materials with renewable and secondary materials is feasible: these materials are disposed of daily by modern society and are therefore constantly available. When produced with secondary resources, these composites contribute to the circular economy (He et al., 2020). Recycled plastics, for instance, are often cited as raw materials that are used or could potentially be used to manufacture BBC for construction (Kazemi Najafi, 2013; Krause et al., 2018). Another standard secondary resource suitable for BBC and building materials manufacture is coal fly ash (Bhatt et al., 2019; Emdadi et al., 2017). However, waste materials and secondary resources may pose risks for human health. In the best case scenario, all types of disposed-of resources should be followed by full risk assessments before their reutilization in supporting building materials design (Sullens et al., 2015); full risk assessments, though, remain rare and expensive (Sullens et al., 2015).

Inspired by the BioHome project “Building materials for affordable housing made from bio-based and recycled resources”, this research identified potential, locally available resources to sustainably supply building materials in South Africa. Following the framework proposed by this project, two types of bio-based building materials were selected. These alternative building materials are partially or fully manufactured with renewable and secondary resources and have been proven in their applications for construction. The investigated building materials are briefly presented in Sections 2.1.1 and 2.1.2 bellow.

2.1.1 Thermoplastic polymer composites

Currently, thermoplastic polymer composites are available for a wide range of outdoor and indoor applications, as construction materials for garden and yard products, in the automotive industry, and as household items and packaging (Hung et al., 2017; Schwarzkopf & Burnard, 2016; Sommerhuber et al., 2015). The most tested formulations of these composites contain wood. Therefore, they are commonly called wood-polymer composites (WPC). The EN 15534-1 definition of WPC describes this as “a product made of the combination of one or several cellulose-based materials with one or several thermoplastic polymer, intended to be or being processed through plastic processing techniques” (CEN European Committee for Standardization, 2014).

In many cases, the wood content approaches 50% of the volume of WPC and is based on byproducts that occur in wood-based industries (Krause et al., 2018; Schwarzkopf & Burnard, 2016). The most utilized polymers for WPC matrix are plastics such as polypropylene (PP), polyethylene (PE) and polyvinyl chloride (PVC) (Sommerhuber, 2016). The environmental performance of WPC has some limitations, because its production partly relies on non-renewable resources; the utilization of recycled thermoplastics for manufacturing WPC is therefore suggested (Krause et al., 2018). An advantage of WPC is its recyclability into new composites (Krause et al., 2018). Figure 4 shows the main raw material necessary to manufacture WPC with secondary LCM and recycled plastic resources.

A) Wood particles (powder)

B) Recycled plastic

Source: Photos by Marco De Angelis

Figure 4 – Basic raw materials for manufacturing wood-plastic composites

2.1.2 Geopolymer composites

Geopolymer composite manufactured with secondary resources are utilized as bricks and masonry components for outdoor and indoor applications. (Maraveas, 2020). Basically, the geopolymer brick-making processes involve combining earth-based materials (e.g. kaolinite, clay, or metakaolin) with water to mold and dry it, obtaining a brick (Maraveas, 2020). These composites can be made from secondary resources such as coal fly and bottom ash and furnace slag (Castaldelli et al., 2013; Emdadi et al., 2016; Rodier et al., 2019; Ye et al., 2018), and therefore offer an alternative to industrial residues (Bhatt et al., 2019). The global occurrence of fly ash as coal combustion residuals (CCR) is estimated to be around 700 million metric tons [mt] annually (Asante et al., 2021; Ferreira et al., 2003), and its availability is becoming attractive and realistic for the building industry as part of its effort to adapt to more resource-efficient construction (Emdadi et al., 2016; Payá et al., 2002; Sarmin et al., 2014).

Researches have proposed the use of agricultural byproducts as a low-cost, environmentally friendly type of raw material for geopolymer brick manufacture (He et al., 2020; Luhar et al., 2019). The most investigated agricultural byproducts for this purpose include sugarcane bagasse (Maraveas, 2020; Ribeiro et al., 2020; Rodier et al., 2019; Sheshmani, 2013), maize crops byproducts (Memon et al., 2020; Nourbakhsh & Ashori, 2010), and ground nut shells (Potadar & Kadam, 2018). Figure 5 shows the main raw materials to manufacture geopolymer composites with secondary resources.

A) Wood powder (left) and ash (right) B) Wood geopolymer composite

Source: Photos by Bright Asante

Figure 5 – Basic raw materials for manufacturing geopolymer composites

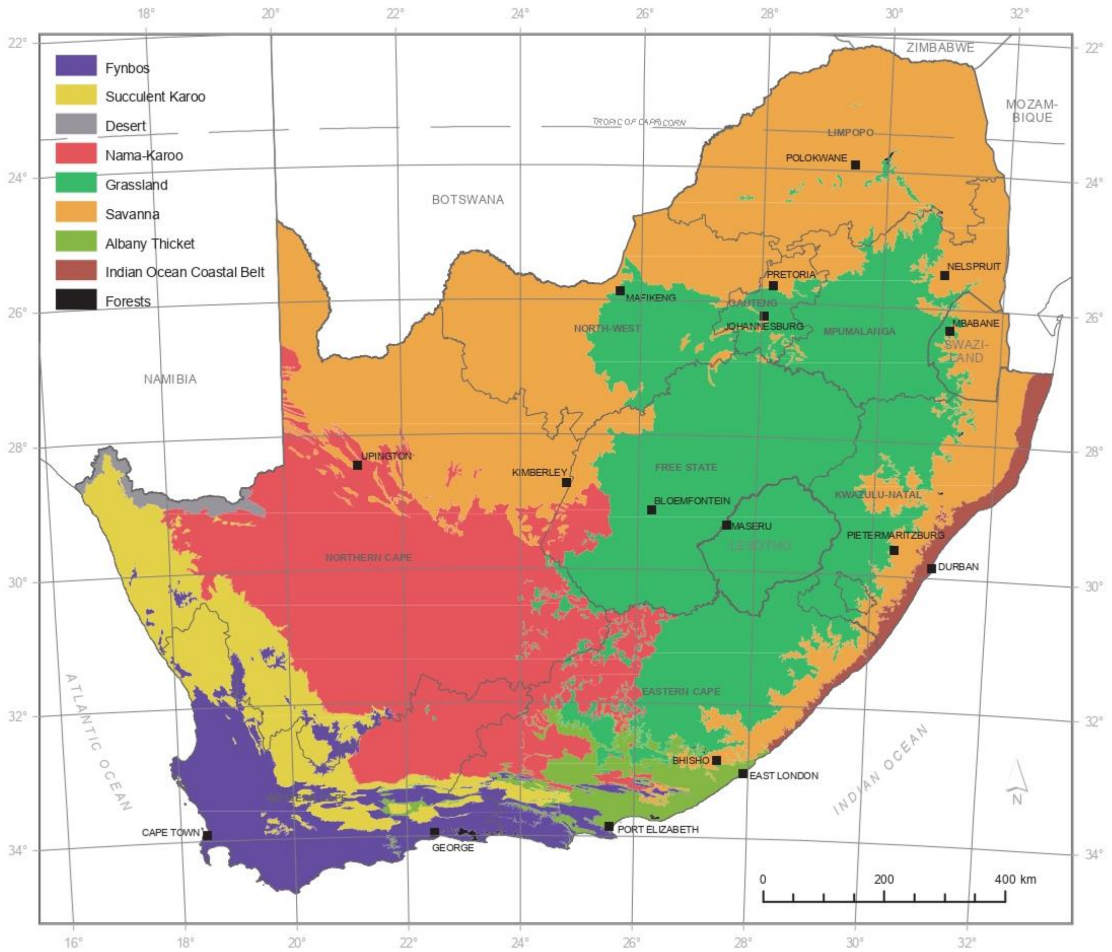
2.2 Monitoring renewable and secondary resources

The alternative building materials proposed by the BioHome project are manufactured with renewable (e.g. wood processing residues, agricultural byproducts, other LCM) and secondary resources (e.g. recycled plastic and fly ash from CCR). The question of how much of these resources is globally available has been the object of different lines of research to be presented here. A more resource-efficient building industry should start at the design stage (Desing et al., 2021), with the identification of locally available, recycled and secondary resources (Kiyanets, 2016), of which they are many (Ogundipe et al., 2021). However, these suitable resources need to be monitored to determine whether their utilization is, in fact, more sustainable than that of non-renewable materials.

The resource monitoring of wood has been the object of studies in multiple European countries (Fonseca, 2010; Mantau, 2015). Wood monitoring methodologies suggests covering raw material flows from forest harvest until final disposal, including during all processing, manufacturing, and recycling steps that may take place in between (Schweinle et al., 2020). Extending wood utilization through its cascading use is preferable. The cascade effect occurs if a resource is transformed into a product and this product is then utilized at least once more after its intended use. Cascading use of forest resources is "the efficient utilization of forests by using [their] processing residues and recycled materials to extend total wood availability" (Essel & Reichenbach, 2016). Regarding food resources, cascade use follows first material use as animal feed (e.g. agricultural byproducts), second use as processed material for other uses (e.g. production of bio-based building materials), third as a source of energy, and finally disposal, where incineration without energy recovery and landfill is prohibited (OVAM, 2015).

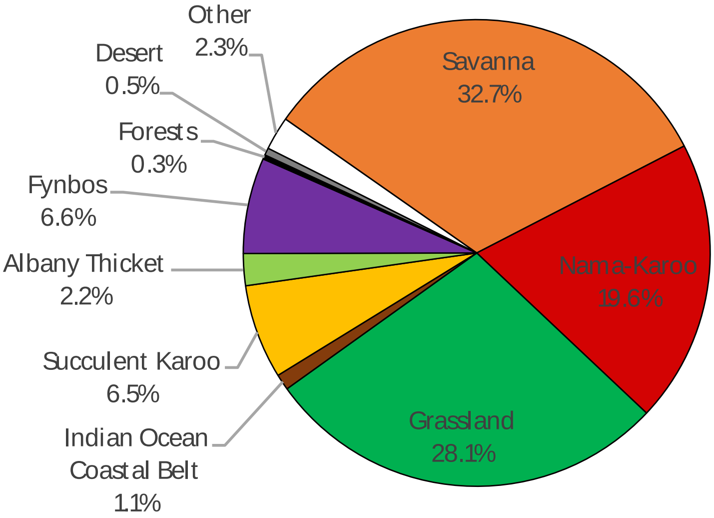
To improve cascading use and resource efficiency, conversion factors are essential. They are also essential while monitoring resources. The forest sector utilizes conversion factors to benchmark the efficiency of production processes, tree growth models, biomass calculations, and estimates of semifinished wood products sales, to cite just a few (FAO et al., 2020; Fonseca, 2010). Accurate and up-to-date conversion factors are decisive in performing robust resource monitoring (FAO et al., 2020). With accurate conversion factors, the volume of secondary wood resources available for bio-based building materials manufacture is quantifiable.

State-of-the-art for resources availability in South Africa will be described in the following. South Africa's territory has 122 million hectare [ha] and its land cover is classified by vegetation type, generally referred to as biomes (Figure 6 and Figure 7). A biome is an area "having similar vegetation structure exposed to similar macroclimatic patterns" (Rutherford et al., 2006). South African biomes such as savanna, *fynbos*, succulent *karoo* and *nama-karoo* have suffered alteration due to the land use change (FAO, 2020).



Source: Vegetation field atlas of continental South Africa, Lesotho, and Swaziland by SANBI (Mucina, 2014)

Figure 6 – Biomes of South Africa, Lesotho, and Swaziland

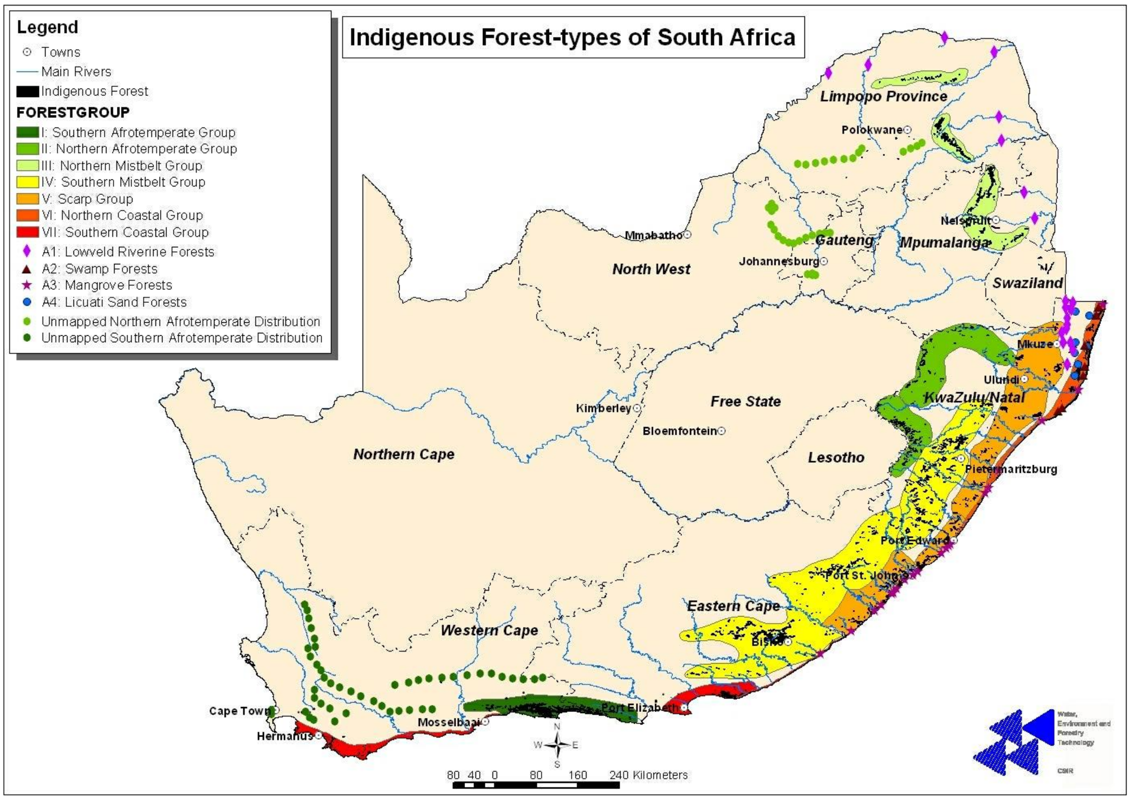


Source: Biomes and bioregions of Southern Africa (Rutherford et al., 2006)

Figure 7 – Relative proportions of biome cover (area) from Figure 6

According to DAFF, the Department of Agriculture, Forestry and Fisheries in South Africa, several areas originally classified as savanna have been transformed into agricultural fields, bare land, or urban areas. Table 7 and Table 8 in the appendix show land cover and land use in South Africa in area per hectare [ha]. The Department of Water Affairs and Forestry in South Africa (DWAF), reported that indigenous forest represents about 0.4 % of the national territory. The FAO defines natural or indigenous forests as “forest areas covered with native species” (FAO, 2018b). Even if this forest type now covers only a small portion of South Africa, it has ecological and conservation value (Malitz, 2003; Mensah et al., 2018).

The South African indigenous forest was originally comprised of endemic and non-endemic *Podocarpus spp.* Popularly known as “Yellowwood”, these species were broadly commercialized as timber in the past, and are now endangered (SANBI, 2020). Local indigenous forests suffered from deforestation and desertification processes due to unsustainable forest management and agricultural field expansion (FAO, 2014b). Figure 8 shows the current cover of indigenous forest by forest type in South Africa.



Source: Classification system for South African indigenous forests (Malitz, 2003)

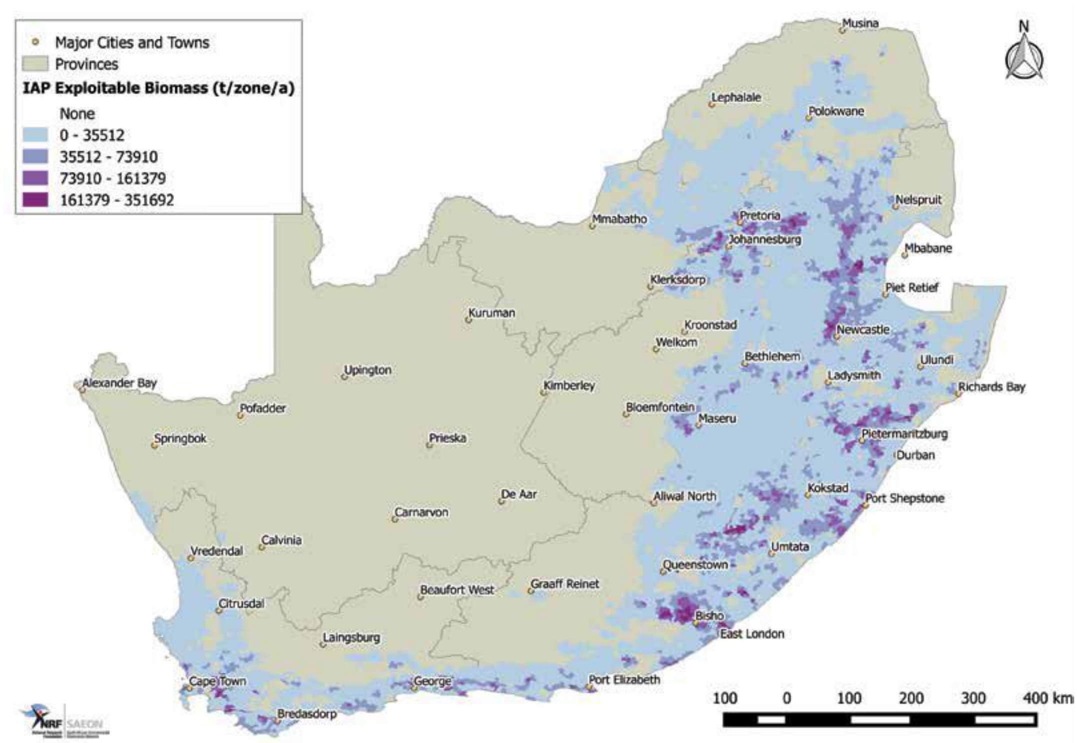
Figure 8 – Indigenous forest classification in South Africa, Lesotho, and Swaziland

To supply national demand for wood resources, South Africa implemented commercial plantation forests. Plantation forests are areas "predominantly composed of trees established through planting and/or deliberate seeding, including coppice from trees that were originally planted or seeded and intensively managed" (FAO, 2020). However, deforestation, agricultural field expansion, and the emergence of plantation forests have facilitated the propagation of invasive alien plants (IAP). IAP introduction was first noticed in 1872 in South Africa, emerging alongside the establishment of plantation forests (Richardson et al., 2020). IAP propagation negatively impacts the environment by reducing the biodiversity of indigenous forests and the regeneration rate of native tree species (Behrens et al., 2007; Gibson et al., 2018; Mbedzi et al., 2018). Additionally, the spread of IAP is related to the reduction of surface water runoff and groundwater (van Wilgen & Wilson, 2018). Considering these aspects, special attention has been given to IAP biological control in South Africa (Lesley Henderson & Wilson, 2017).

- The Alien and Invasive Species Regulations (A&I Regulations) published in 2014 in South Africa regulate IAP biological control operations (van Wilgen et al., 2020).

- The Working for Water Information Management System (WIMS) monitors IAP propagation and designates government funds to incentivize biological control on privately-owned land (Richardson et al., 2020).

The issue of IAP propagation has been investigated by the BioEnergy Atlas (BEA) and the Southern African Plant Invaders Atlas (SAPIA), which has recorded information on the national extent of the spread of alien plants since 1994 (Lesley Henderson & Wilson, 2017). The geographical distribution of IAP in South Africa, Swaziland, and Lesotho monitored by SAPIA was compiled on the BEA study in order to provide a map of invasion, as shown in Figure 9.



Source: BioEnergy Atlas (BEA) for South Africa and Southern African Plant Invaders Atlas (SAPIA) (L. Henderson, 2007; Hugo, 2016)

Figure 9 – Distribution of invasive alien plants as standing biomass in South Africa, Lesotho, and Swaziland

The clearing of IAP is mandatory in South Africa. In 2017, SAPIA reported that the biological control of IAPs has been successful for some plants, such as *Acacia spp.* (L. Henderson, 2007; Lesley Henderson & Wilson, 2017). However, information on the volume of IAP readily available remains unclear. BEA has estimated the potential volume of IAP harvest and other biological resources locally available and suitable for electricity generation in order to investigate renewable alternatives of power generation for South Africa (Hugo, 2016). Currently, electricity generation in the country is highly dependent on coal. The great volume of various residues occurring inside national coal-fired power stations coupled with poor waste management in South Africa is concerning. According to the DEA, the Department of Environmental Affairs, 90 % of residual "fly and bottom ash" from CCR are annually landfilled in South Africa (DEA, 2018). The second major electricity source in South Africa is based on renewables (7.9 %). According to SANEDI (South African National Energy Department Institute), biomass supplied 93 % of the total renewable energy supply in the country in 2015. SANEDI follows IEA (International Energy Agency) terminology, that defines solid biofuels or solid biomass as "any plant matter used directly as fuel or converted into other forms before combustion", which includes charcoal (Pelkmans & Bali, 2018).

BEA drew attention to a limited biomass increment in South Africa and concluded that a mix of agricultural and forestry residues and the harvest of IAP are best candidates to locally supply biomass for energy (Hugo, 2016). Though this plant biomass is important to alleviating coal dependency in South Africa, thousands of metric tons of these materials are landfilled in the country annually (DEA, 2018). Incorrect waste disposal leads to sanitation issues and contamination outbreaks, causing health issues in SSA countries (Zerbo et al., 2020). To prevent the landfilling, a task force agreed to increase local legislative environmental taxes in South Africa (Olayiwola et al., 2021), but effective waste management that adds value to secondary resources remains necessary (Adenuga et al., 2020). In addition to the inefficient waste collection and classification, there is a lack of a market for secondary resources in several African countries (Troschinetz & Mihelcic, 2009).

The BEA proved a relevant investigation about resource monitoring in South Africa and consequently its recommendations assisted in the methodological design of the present investigation. However, the focus of this research is to find suitable renewable and secondary resources for material use, not for energy purposes. The next chapter will present the raw material categories investigated, based on the most up-to-date resources in South Africa.

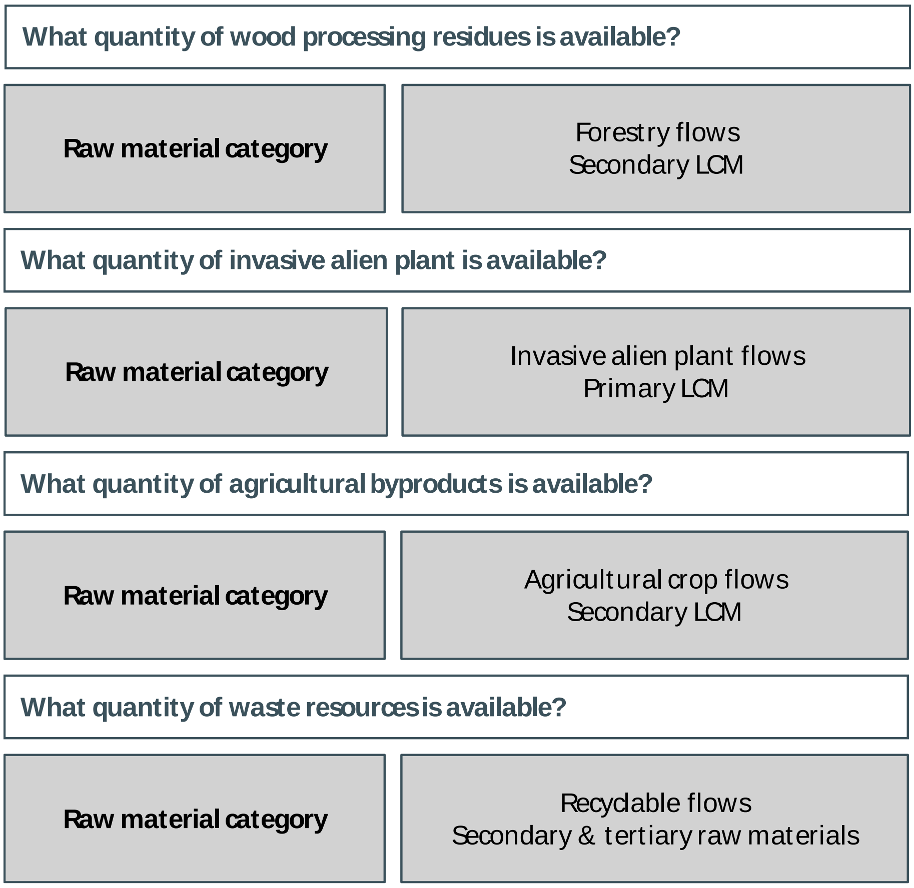
3 MATERIALS AND METHODS

South Africa has a wide range of resources suitable for manufacturing bio-based building materials, though little is known about the real available volume of these resources. This research selected four different renewable and secondary resources in South Africa to investigated their availability. Identifying secondary resources, as opposed to primary ones, was preferred. Selected resources were aggregated into categories of raw material. Each raw material category was investigated individually via resource balance and material flow analysis (MFA). The MFA results were designed using the software e!Sankey.

This chapter, Materials and Methods, presents all information collected and the methodological approach adopted to estimate available volumes of each raw material category. First, each raw material category is introduced. Then, information on sources and consumption of the selected raw materials are presented. This research was carried out based on data from 2018. Finally, the methodological approach chosen to carry out individual MFA is described. The complete consulted databases for this study are available as an appendix.

3.1 RESOURCES FOR ALTERNATIVE BUILDING MATERIALS IN SOUTH AFRICA

This study investigated available resources in South Africa suitable for the manufacture of WPC and geopolymer composites there. The resources were grouped into four raw materials categories as presented in Figure 10. Three of these categories investigated the volumes of lignocellulosic materials (LCM) while one investigated the volume of secondary materials. The methodology and results of each resource monitoring are presented in the same raw material categories in the following sections.



Notes: LCM = lignocellulosic materials

Figure 10 – The four raw material categories investigated in South Africa in this study

Different MFA methodologies were adopted according to each monitored raw material category. Each raw material category generated an individual MFA, presented separately in the Results and Discussion chapter. In addition, nine interviews were carried out with representatives of companies involved in the forestry and agriculture sectors in South Africa. The interviews occurred between October and December 2019, were conducted in person or online, and did not follow a pre-defined questionnaire.

3.1.1 Forestry flows

The raw material category Forestry flows represents the available volume of secondary resources obtained from forests in South Africa, specifically the volume of wood processing residues (WPR). WPR occurs during the processing of wood and manufacturing of semifinished and finished wood products (Saal et al., 2022). The estimation was conducted according to the methodological approach proposed by Mantau in 2015, dubbed "wood flow analysis", or WFA. This approach starts with the design of a resource balance calculation using the example of the raw material wood. The wood resource balance is based on the volume of semifinished products and is therefore feasible if this volume is known (Mantau, 2015). The basic resource balance established for South Africa is presented in Table 1.

Table 1 – Basic wood resource balance for South Africa

Sources	**Uses**
Primary resource	**Material use**
Roundwood and forest residues • Indigenous forest • Plantation forest	Pulp industry Wood industry • Saw & plywood mill • Wooden panels • Mining timber • Wooden poles
Secondary resource	**Energy use**
Wood processing residues • Black liquor • Sawmill byproducts • Wood chips Energy products • Wood charcoal • Wood pellets	Producers of wood fuels • Wood charcoal • Wood pellets Industrial firewood Households

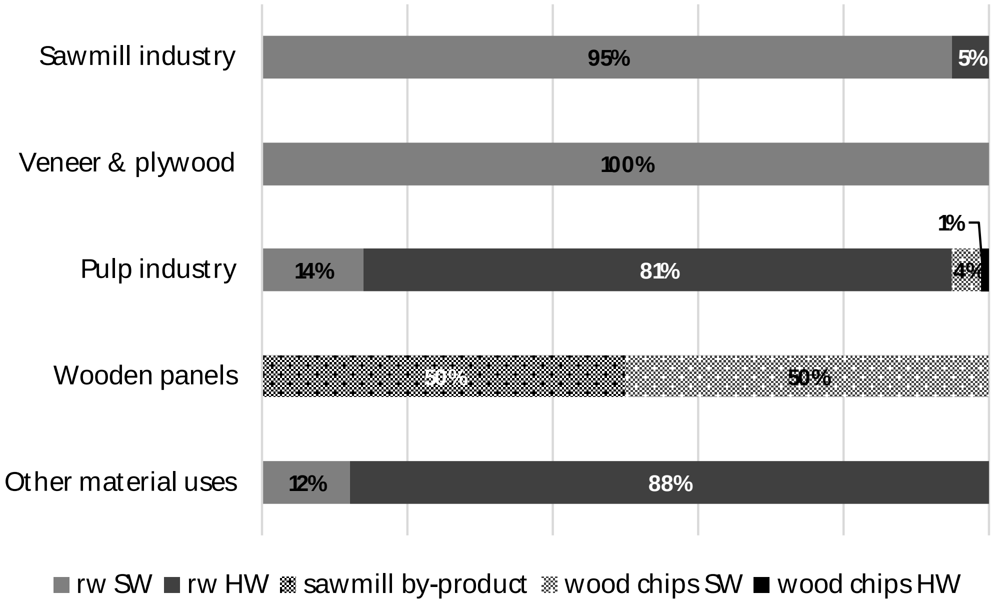
Notes: Roundwood is wood in its natural state as felled, with or without bark. It may be round, split, roughly squared, or in other forms (FAO, 2022)

Source: Expanded on by the author following the basic wood resource balance proposed by the wood flow analysis methodology (Mantau, 2015).

The right side of the basic wood resource balance (Table 1) lists uses of wood in South Africa and classifies this utilization into either material use or energy use. The left side presents primary and secondary sources of wood available in South Africa. As mentioned, the volume of semifinished wood products is the starting point for calculating a wood resource balance. The Department of Agriculture, Forestry and Fisheries (DAFF) publishes the production volumes of semifinished wood products manufactured in South Africa, and the Paper Manufacturers Association of South Africa (PAMSA) publishes further information regarding the national volume of wood pulp production. At the international level, production, import, and export of wood in rough and semifinished wood products is compiled and published by the Food and Agriculture Organization (FAO). Volumes are reported in cubic meters [m³] and per 1,000 kilogram, i.e. metric ton [mt]. No volumes of semifinished wood products manufactured with roundwood from indigenous forests were reported. Therefore, the estimation of WPR available in South Africa is considered to have originated from plantation forest. The volumes of semifinished wood products reported by DAAF, PAMSA, and FAO are presented in the appendix (Table 9, Table 12, Table 13 and Table 14). The import and export of roundwood and semifinished wood products is presented in the appendix in Table 15.

The next step to fulfill the requirement for the wood resource balance calculations is to assess the volume of solid wood needed to produce a given semifinished wood product. Conversion factors have been utilized to disclose the volume of wood needed to manufacture 1 (one) [m³] or [mt] of a given semifinished product (Fonseca, 2010). Consequently, to estimate how much WPR occurs during the wood processing, conversion factors are necessary. Specific conversion factors for South Africa were obtained from the “Forest product conversion factor” report (FAO et al., 2020) and are presented in Table 16, 17, and 18 in the appendix.

The estimation of wood consumption for material use was carried out according to the volumes of semifinished wood products reported by DAFF, multiplied by conversion factors. This multiplication results in the volume of roundwood under (or without) bark in [m³], also referred to as solid wood equivalent (swe). Roundwood is the wood removed in its round form (log), split, roughly squared, or in some other form (FAO, 2022). At this point, it is important to emphasize that the estimated volume of wood consumption is not exclusively supplied by roundwood, but by mix of wood resources (e.g., WPR as sawmill byproducts, wood chips, slabs, sawdust, etc.). Therefore, the next step is to verify the utilized mix of wood resources of each wood consumer. The main challenge here is data availability and data reliability (Mantau, 2015). The wood resource mix utilized by wood consumers in South Africa has been collected in the technical literature and is presented in Figure 11.



Notes: rw = roundwood; SW = softwood; HW = hardwood

Source: Department of Agriculture, Forestry and Fisheries (DAFF); Food and Agriculture Organization (FAO); Paper Manufacturers Association of South Africa (PAMSA) (DAFF, 2018; FAO, 2018a; PAMSA, 2018)

Figure 11 – Input of wood resource mix demanded by each wood consumers (material use) in South Africa

According to literature, the saw and plywood mills in South Africa consumed exclusively roundwood during the data collection period. The same was verified for the segment entitled Other material uses, which is fully represented by mining timber and wooden pole production in South Africa. PAMSA affirmed that the national pulp industry consumes roundwood and wood chips of both soft-and hardwood. According to PAMSA, the wood consumption by the pulp industry consisted of 95 % roundwood. The remaining 5 % was represented by wood chips, 83 % of which stemmed from softwood species and 17 % from hardwood species (PAMSA, 2010). No official information about the wood resource mix utilized by the industrial segment wooden panels was available. For calculation purposes, it was assumed that this industrial segment exclusively demanded wood chips (50 %) and WPR (50 %).

Given that saw and plywood mills demanded 100 % roundwood, their final wood consumption was multiplied by 1 (one), which results in the volume of swe demanded by these consumers. However, in the case of the pulp industry, final wood consumption was multiplied by 0.95, which resulted in the volume of roundwood demanded. Subsequently, the final total wood consumption by the pulp industry was again multiplied by 0.05, which resulted in the volume of wood chips utilized. This step was repeated for all wood consumers, according to the input of wood resource mix informed by literature and assumptions.

A great part of the estimated volume of wood consumption for material use is transformed into semifinished wood products, but also into WPR. The volume of WPR and its characteristics depend on the adopted techniques and technological developments of wood-based industries (Saal et al., 2019). For instance, during the production of veneer and plywood, a specific WPR occurs, called peeler core. The peeler core is the residual volume of a piece of rotary-peeled roundwood (Fonseca, 2010). To rotary peel wood veneer, roundwood must be held and pivoted by lathe chucks. In this situation, the minimum roundwood diameter at which veneer can no longer be peeled is usually controlled by the diameter of the chucks (Fonseca, 2010). According to the conversion factors for South Africa (Table 17), 47 % of the wood resource input for veneer and plywood occurred as WPR. The WPR occurrence by sawmill in South Africa followed material balance values informed in Table 17 as well. For Other material uses, it was assumed that 15 % of wood input occurred as WPR.

A particular type of WPR occurring within the pulp industry is black liquor. The literature has reported that 50 % of the roundwood input at pulp industries for sulphate wood pulp is converted into black liquor (Briggs, 1994; Clark et al., 2010; FAO et al., 2020; Fonseca, 2010). Mechanical wood pulp presents a yield of 94 % and dissolving a yield of 35 % (Briggs, 1994; FAO et al., 2020). Only the volume of black liquor was taken into consideration, because this WPR is suitable for further energy uses (IEA, 2018; PAMSA, 2010, 2018). In fact, a small share of black liquor flows back into pulp production (Essel & Reichenbach, 2016), but this study considered its entire volume to be utilized for energy generation.

As presented in Table 1, the wood demand for energy use in South Africa is arranged into three categories: producer of wood fuels, industrial firewood and households. Firewood is described as “fuel wood, in logs, in billets, in twigs, in faggots or in similar forms” for energy use (FAO, 2022). The producer of wood fuels category assessed wood demand for the production of wood charcoal and wood pellets, and it was assumed that charcoal production had demanded exclusively roundwood. According to official South African statistics, to produce 1 (one) ton of charcoal, 10 m^3 of roundwood is needed (DWAF, 2004). It was assumed, too, that wood charcoal was produced exclusively with hardwood (non-coniferous). Values for wood charcoal (295,500 mt) and wood pellets (5,000 mt) production in South Africa were collected on the FAO statistical database (Table 14). Unlike wood charcoal production, wood pellets are not produced from roundwood, but from WPR occurring at saw and plywood mills. To estimate wood demand for pellet production, it was considered that 1 (one) [mt] pellets consumes 2.25 m^3 of solid wood, following an average informed by statistics from Asian countries (FAO et al., 2020).

The industrial firewood category represents the wood volume transformed into black liquor in pulp mills added to the volume of wood demanded for heat and steam production by other industries. The household category represented wood consumption for cooking and heat production. The total firewood production reported by FAO in 2018 (12,025,764 million m^3; Table 14) was considered to represent the total wood demand for energy use in South Africa. In other words, the firewood production reported by FAO was divided into the three categories of wood consumption for energy use, as presented in Figure 12. The share of firewood consumption by industries and households was based on the volumes of the World Energy Balance publication by the International Energy Agency (IEA). IEA informs about the power generation from solid biofuels worldwide and collected data for South Africa (Table 19). According to IEA, both industrial firewood and households demanded the same quantity of solid biofuels.

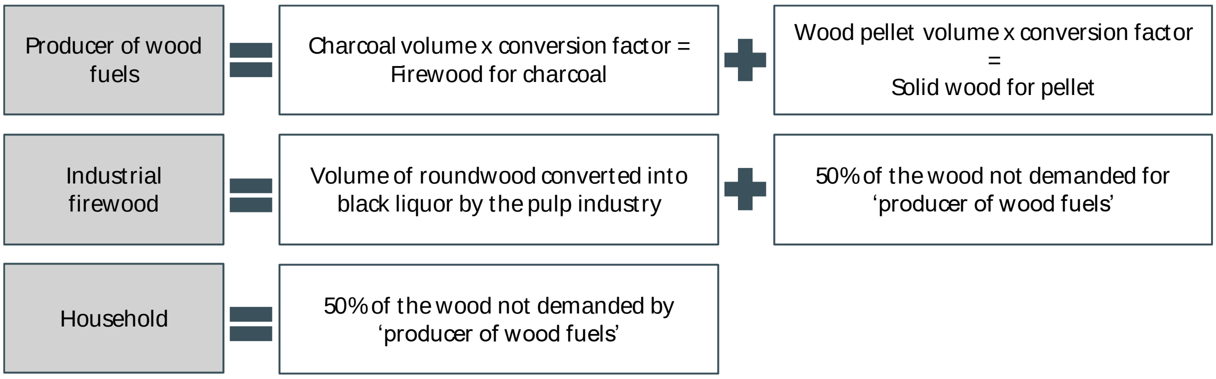


Figure 12 –Input of wood resource mix demanded by wood consumers (for energy use) in South Africa.

The wood resource balance results fulfill the requirements for designing the WFA. Additionally, volumes of import and export collected in the FAO statistical database 'Forestry production and trade' (Table 15) were also considered. The wood resource balance was calculated utilizing the volumes in million cubic meters [M m^3]. However, the MFA was built on e!Sankey with values in millions of metric tons [M mt]; for this calculation, values for wood basic density were utilized (Table 16).

Finally, to verify whether plantation forests were able to supply the total quantity of roundwood demanded in South Africa in 2018, their sustained production was estimated. The sustained production by forests is obtained through the multiplication of forest-covered area by the tree mean annual increment, or MAI. The MAI represents the tree increment during a period of one year and is reported in cubic meters per hectare [m^3/ha]. The plantation forest area in South Africa was reported in 10,000 square meters [m^2], labelled hectares [ha], and is presented in Table 20 in the appendix.

The sustained production reveals how much roundwood could have been sourced from forests, and the results are given in a ratio of m^3/ha per year [m^3/ha a^{-1}]. Forest production by indigenous forest was not estimated because the area covered by each tree species and its respective MAI were lacking. Figure 13 summarizes the most relevant data and methodological approach to carry out an MFA for forestry flows:

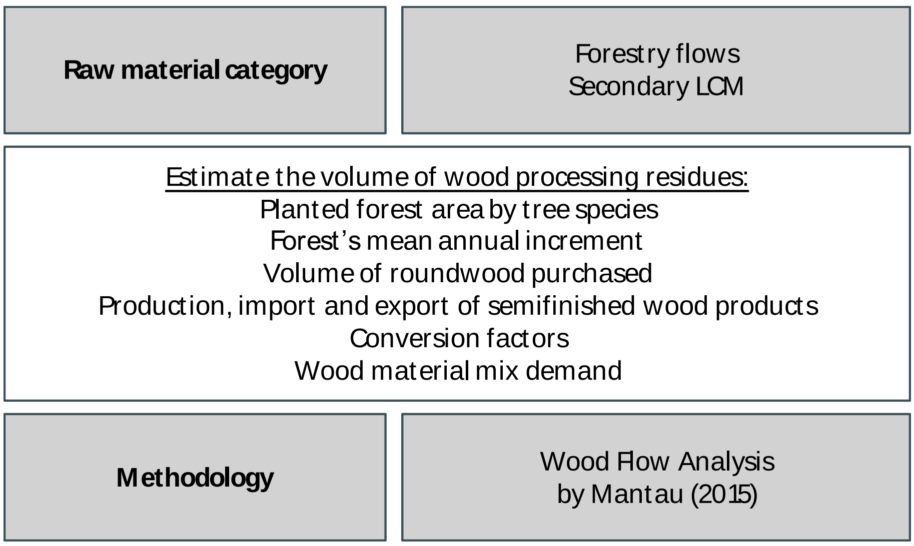


Figure 13 – Summary of available data and methodological approach to carry out a material flow analysis for the raw material category of Forestry flows in South Africa

3.1.2 Invasive alien plant flows

The areas invaded by IAP represent a relevant source of LCM in South Africa, if their biological control by harvest operations takes place (Hugo, 2015). Therefore, the raw material category Invasive alien plant flows captured the potential volume of primary lignocellulosic resources obtained from harvest of invasive alien trees in South Africa. IAP are defined as plants which "sustain [their] self-replacing populations over several life cycles, produce reproductive offspring, often in very large numbers at considerable distances from the parent and/or site of introduction, and have the potential to spread over long distances" (van Wilgen & Wilson, 2018).

It is known that more than 80,000 hectares have been affected by alien plants in South Africa, as shown in Table 21 in the appendix. The distribution records on IAPs published in the Southern Africa Plant Invader Atlas (SAPIA) is considered at this point the most comprehensive data source on the IAP distribution in the country (Rouget et al., 2015). To design the MFA for this raw material category, an estimation of IAP availability published in 2016 by the BEA study that assessed the potential harvest volume of woody biomass from invaded areas in South Africa was utilized: it reported an annual availability of 11.30 teragrams [Tg = 10^{12} gram = 1,000,000 mt]. This estimate included the tree species listed in Table 21 and occurring bamboo species, which were introduced to South Africa from the time of the intra-African migration and the arrival of Europeans, and have been appointed a potential source of biomass (Canavan et al., 2019; Canavan et al., 2021).

The BEA estimate was based on the annual IAP increment over a period of more than 20 years of harvest operations. However, from the total potential IAP volume reported by BEA, only 71 % was considered to be readily available for further uses (Hugo, 2016). Although, the BEA stated that the possibility of performing manual collecting of harvest residues left on the fields could increase this potential volume. Following BEA study assumptions, the MFA for this raw material category assumed that an extra IAP volume is obtainable if 36 % of the residues left on the fields were manually collected.

Because IAP are an important source of renewable energy for South Africa, it was determined that only 50 % of LCM sourced by IAP were readily available for manufacturing building materials. Figure 14 summarizes the available data set and methodologies applied for this purpose:

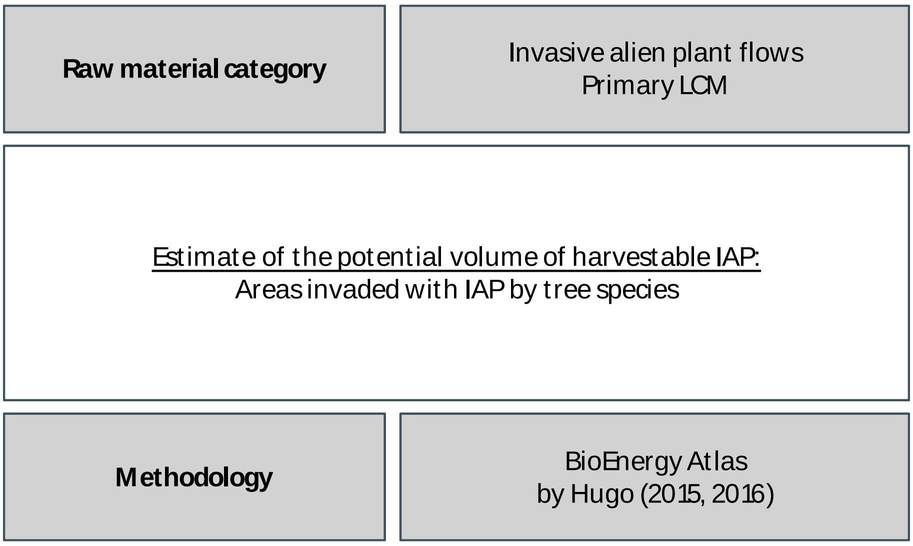


Figure 14 – Summary of available data and methodological approach to carry out a material flow analysis for the raw material category of Invasive alien plant flows in South Africa

3.1.3 Agricultural crop flows

Another relevant source of LCM in South Africa occurs in agricultural fields (Hugo, 2016). The raw material category Agricultural crop flows assessed the annual volume of agricultural byproducts available in South Africa in 2018. Agricultural field areas in South Africa are monitored by the Census of Commercial Agriculture. In 2018, an area of 46.4 million hectares was under agricultural use in the country, but only 12.9 % of it was dedicated to field crop production. Table 8 in the appendix shows the detailed composition of land under agricultural use in South Africa in 2018. The estimated of the amounts of agricultural byproducts were calculated according to the land use dedicated to agricultural purposes and their annual production. Table 23 in the appendix shows the land use dedicated to agricultural purposes in South Africa, according to its economic activity.

The total land area of 46.4 million hectares was reported to be under commercial agriculture use, of which a share of 78.7 % was represented by grazing land dedicated to livestock and game farming (Stats SA, 2017). Grazing land was not accounted as a source of agricultural byproducts for this study. The other share of 16.4 %, classified as arable land (7.6 million hectares), is divided into other four different uses: crop production, cultivated pastures, temporarily fallow and other (Stats SA, 2017). The MFA of agricultural byproducts considered only the area dedicated to crop production as a constant source of secondary LCM. This area is classified according to the crop type: grains and cereals, oil seeds, or other crops.

The mosaic of field crops in South Africa yields a variety of byproducts. For instance, while the processing of maize crops produces stalks, cobs, and husks, the processing of winter cereals provides wheat, barley, and oat straw. However, the MFA for this raw material category made no distinction between each agricultural byproduct, but instead focused on the readily available total volume. If agricultural byproducts occurred during the processing of horticultural crops, they were not considered in this study. Information on annual field crop production is reported by SAGIS, the South African Grain Information Service, and by DAFF. Values are presented in the appendix in Table 22.

Agricultural byproducts are globally in demand both for food security and soil protection (Batidzirai et al., 2016; Hugo, 2016; Mohlala et al., 2016). Therefore, to estimate the available volume of agricultural byproducts per field crop, conversion factors as shown in

Table 24 in the appendix have been adopted. The estimated available volume of agricultural byproducts in South Africa was calculated with the Bioenergy and Food Security (BEFS) rapid appraisal. The BEFS rapid appraisal is a free tool for assessing the availability of agricultural byproducts and other biomasses (FAO, 2014a). The present study utilized the BEFS natural resources module specifically for agricultural byproduct estimation. The collected values and conversion factors were inserted to the appraisal tool to assess the volume of byproducts, considering the country's needs for food, livestock feed, and other material uses such as soil maintenance.

Summarizing, the BEFS multiplies the production volume of each agricultural field crop by the share of residues occurred, as detailed in Table 24 in the appendix. This result is again multiplied by the share of residues dedicated to soil maintenance and to animal feed. Finally, the sum of the residues dedicated to soil maintenance and animal feed is subtracted from the total volume of agricultural residues. Figure 15 described the steps for estimating the volume of agricultural byproducts carried out with the BEFS and conversion factor from Table 24 (in the appendix).

Areas where fruit trees such as oranges and apples are grown were studied as a source of LCM because younger trees generally replace older ones. This replacing operation may supply woody biomass as well. For more information, four fruit producers were interviewed. Export and import volumes of byproducts were not considered, because no information was available. Therefore, it was assumed that agricultural residues remained inland. Figure 16 summarizes the available data set and methodologies applied for the MFA of the raw material category of agricultural crops flows.

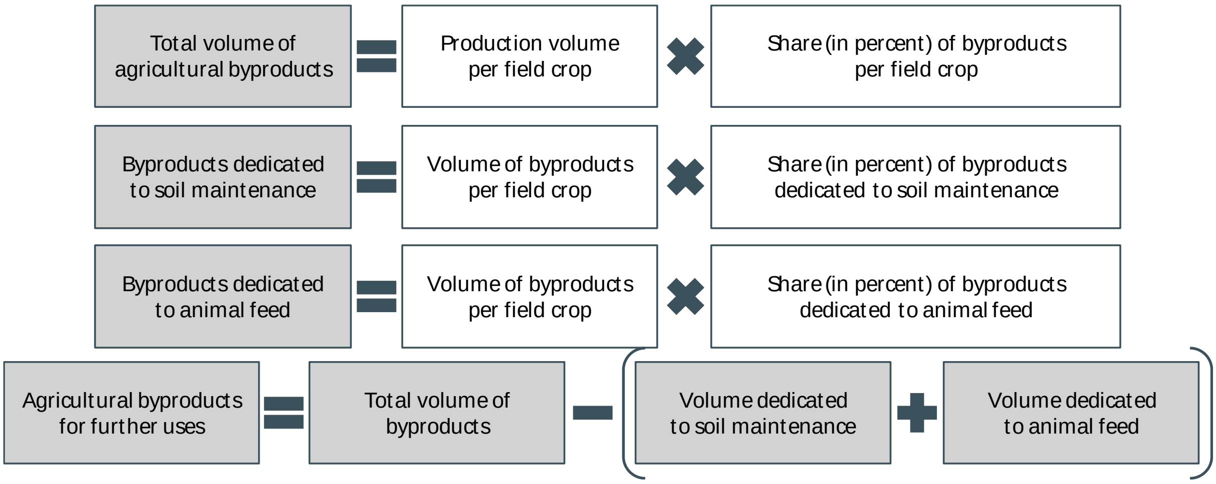


Figure 15 – Schematic explanation of the calculation to estimate volume of agricultural byproducts in South Africa in 2018, carried out on the tool Bioenergy and Food Security (BEFS).

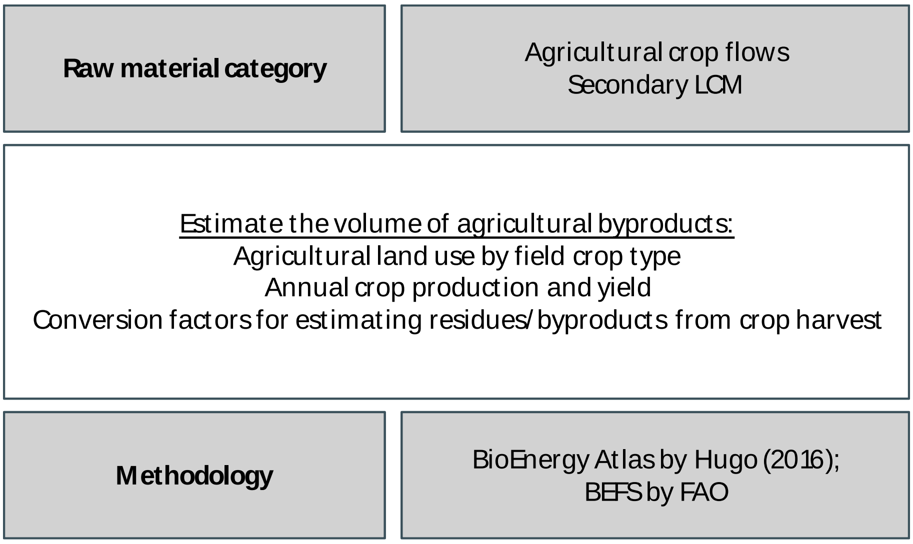


Figure 16 – Summary of available data and methodological approach to carry out a material flow analysis for the raw material category of Agricultural crops flows in South Africa

3.1.4 Recyclable flows

This raw material category considers the composition of waste in South Africa in order to investigate suitable secondary resources for manufacturing alternative building materials. These volumes were estimated according to the Department of Environmental Affair (DEA) reports. Published by DEA, the latest State of Waste Report (SoWR) distinguished the volume of waste and its composition into two main categories: general waste and hazardous waste (DEA, 2018). The DEA considers general waste to be “waste that does not pose an immediate hazard or threat to health or to the environment”, and hazardous waste is “any waste that has a detrimental impact on health and the environment and includes hazardous substances, materials or objects”. According to the DEA, South Africa generated around 108 million mt of all types of waste in 2011, and 90 % of this volume was landfilled. Types of waste and their volumes are presented in Table 2.

The types of waste investigated in this study were plastics, ash and slag. Fly and bottom ash occur inside coal-fired power plants, boilers, and incinerators, and slag is a waste stream occurring during iron and steel production (DEA, 2012, 2018). A DEA estimate appointed that, for each metric ton [mt] burned coal, an average of 274 kg of ash occurred in South Africa (DEA, 2018). The volumes of selected waste resources are shown in Table 25 in the appendix. In addition to the waste generation, the DEA reported import and export volumes as well as recycling and recovery rates for all types of waste. Even if the volume of secondary and tertiary wood resources disposed of through demolition and urban gardening activities were reported, this volume was disregarded in this MFA. This consideration was made because this type of lignocellulosic waste was reported to remain or be reused on-site, burned, or landfilled (DEA, 2012, 2018).

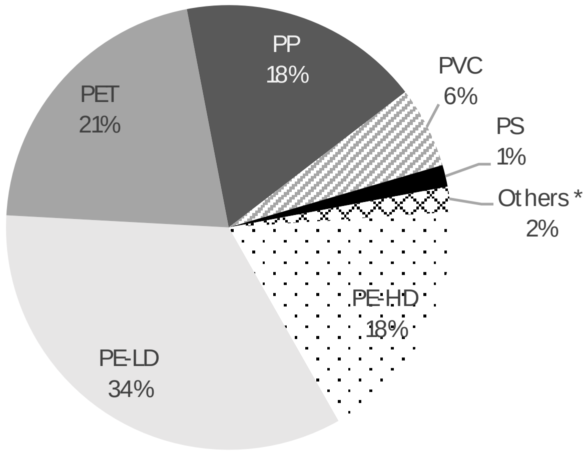
Table 2 – Reported types of waste in South Africa

General Waste	Hazardous Waste
Waste type	
Municipal	Gaseous
Commercial and industrial	Mercury-containing
Fly ash and dust	Batteries
Bottom ash	POPs
Slag	Inorganic
Organic waste	Asbestos-containing
Construction & demolition	Waste oils
Paper	Organic halogenated and/or sulphur containing solvents
Plastic	Organic halogenated and/or sulfur containing waste
Glass	Organic solvents without halogens or sulfur
Metals	Other organic waste without halogen or sulfur
Tires	Tarry and Bituminous
Other	Brine
	Fly ash and dust from miscellaneous filter sources
	Bottom ash
	Slag
	Mineral
	WEEE
	Health Care Risk Waste
	Sewage sludge
	Miscellaneous

Notes: Types of waste underlined were considered for the recyclable material flows analysis; POPs = Persistent Organic Pollutants; WEEE = Waste of Electric and Electronic Equipment

Source: Department of Environmental Affairs (DEA, 2018)

Additional information on the composition of plastic disposed of in South Africa was gathered via the private company Plastics SA. According to Plastics SA, common plastic wastes in South Africa are those containing polyethylene terephthalate (PET), polyvinyl chloride (PVC), low-density polyethylene (LDPE), high-density polyethylene (HDPE), polypropylene (PP), polystyrene (PS), and others (Plastics SA, 2018). In 2018, South Africa recycled 352,000 mt of disposed-of plastic into secondary raw materials. The composition of types of plastic recycled in South Africa in 2019 is presented in Figure 17.



Notes: PET = polyethylene terephthalate; PVC= polyvinyl chloride; LD = low density; HD = high density; PP= polypropylene; PS = polystyrene

Source: Plastics South Africa (Plastics SA, 2018, 2019)

Figure 17 – Types of plastics recycled in South Africa in 2019

The MFA for recyclable materials made was built into two main types of waste, general and hazardous. The MFA followed the simple law of mass conservation, in which the mass that enters the system either leaves the system or is accumulated within it (Brunner & Rechberger, 2016). Mathematically, the material balance for a system is as follows:

$$\sum_{k1} m\ input = \sum_{k0} m\ output + m\ storage \quad (1)$$

'M' is the mass, 'input' is the mass flow entering the system, 'output' is the mass flow leaving the system, and 'storage' represent the mass staying or stocked within the system boundary. Figure 18 summarizes the available data set and methodologies applied for the MFA of recyclable flows category of raw materials.

Raw material category	Recyclable flows Secondary & tertiary raw materials
Estimate of the volume of general waste volume: Fly ash and dust, bottom ash, slag and plastic Estimate of the volume of hazardous waste: Fly ash and dust from miscellaneous filter sources and bottom ash	
Methodology	MFA of plastic in Thailand; by Bureecam, Sungsomboon, Chaisomphob (2017)

Figure 18 – Summary of available data and methodological approach to carry out a material flow analysis for the raw material category of Recyclable flows in South Africa

4 RESULTS AND DISCUSSIONS

Growing population and urbanization pressures in South Africa are serious concerns, especially as they relate to the issue of scarcity of essential resources. To avoid resource shortages, the reuse, repair, and recycling of materials is helpful. For instance, manufacturing building materials with renewable and secondary resources is recommended (Asdrubali et al., 2015; Ben-Alon et al., 2019; Gupta, 2017; Hildebrandt et al., 2017). South Africa has a wide range of renewable resources, including LCM and recyclable waste materials such as plastics, ash, and slag. These local resources are suitable for manufacturing bio-based composite (BBC) for construction purposes and thus would aid the country in adapting to rapid urbanization. To establish BBC manufacturing, a constant supply of these raw materials is necessary. Therefore, the local monitoring of raw material availability is useful.

This chapter presents the results of the MFA carried out for the four categories of raw materials suitable for manufacturing WPC and geopolymer composites in South Africa in 2018. MFA results support the promotion of cascading use of resources, as it monitors material flows. Based on the concept of waste hierarchy, this study preferred to identify secondary rather than primary raw materials. This chapter presents the results and proposes discussions of the most relevant sources of raw materials for manufacturing alternative building materials in South Africa.

4.1.1 Forestry flow analysis

The forestry flow category estimated the volume of secondary wood resources, so-called WPR, occurring during the mechanical processing of wood in South Africa in 2018. A wood resource balance calculation was carried out and the results are presented in Table 3. The right side of the resource balance lists the wood consumers (uses); the volume of wood to energy use is highlighted in gray. The left side presents the sources of wood aggregated into primary and secondary resources. Volumes are reported in millions of cubic meters [M m³].

Table 3 – Wood resource balance for South Africa in 2018

Source			Uses		
	[M m³]	*[%]*		[M m³]	
Primary wood resource	∑	***77.2***	*12.4*	3.7	Sawmill industry
Roundwood	23.3	*77.2*	*0.2*	0.1	Veneer sheets/plywood
Bark	0.0	*0.0*	*32.0*	9.7	Pulp industry
Secondary wood resource	∑	***13.0***	*7.5*	2.3	Wooden panels
Sawmill byproducts	1.1	*3.8*	*4.1*	1.1	Other material uses
Wood chips	1.6	*5.4*	*9.8*	3.0	Producer of wood fuels
Black liquor	1.1	*3.8*	*18.9*	5.7	Industrial firewood
Solid wood fuel • wood charcoal • wood pellets	3.0	***9.8***	*15.1*	4.5	Household firewood
Sum	**30.1**	***100***	***100***	**30.1**	**Sum**

According to the results obtained from the wood resource balance calculation, South Africa demanded at least 23.3 M m³ of primary wood resources in 2018. The greatest volume of wood consumption was for material use by local wood-based industries. The mechanical processing of wood enabled the same wood-based industries to supply secondary wood resources, or WPR. The volume of WPR was demanded for further uses, such as in the manufacturing of wooden panels and for energy use, e.g. wood pellet production. However, the assumption that plantation forests fully supplied the wood consumed in South Africa in 2018 was not confirmed. The sustained production calculated for plantation forests in the country reveals that this type of forest could have supplied no more than 21.8 million m³ of roundwood, as shown in Table 4. This volume of potential supply of roundwood by South

African plantation forest is lower than the amount of wood consumption estimated by this study. Consequently, this indicates that wood resources outside those supplied by plantation forests were demanded as well. Unfortunately, the sustained level of production by indigenous forest was not calculated, because the information needed for this was not available.

Table 4 – Sustained production by plantation forests for selected tree species in South Africa in 2018

Potential annual supply of roundwood	**Volume** [m^3 $year^{-1}$]
∑ Softwood	**8,274,226**
Pinus patula	4,050,001
Pinus elliotti	2,401,833
Pinus radiata	639,112
Others	1,183,280
∑ Hardwood	**13,571,460**
Eucalyptus spp.	12,817,584
Acacia (Wattle)	753,876
∑ Sustained production	**21,845,686**

DAFF reported that wood consumers in the country purchased a total volume of 17.7 M m^3 of roundwood from plantation forests in 2018, as detailed in Table 10 and Table 11 in the appendix (DAFF, 2018). The reported volume of roundwood by DAFF was lower than the estimated wood consumption in this study (Table 3). However, this information is not enough to state that the extra volume obtained in the resource balance calculation (5.6 M m^3) was supplied by indigenous forests. It is highly possible that indigenous forests supplied wood resources for local wood-based industries in South Africa. Nevertheless, it is not possible to identify how much roundwood the indigenous forests did in fact supply, because information was lacking. Indeed, the volume of roundwood purchased by wood consumers reported by DAFF in 2018 could not have been fully supplied by plantation forests.

The wood consumption for material uses in South Africa in 2018 was led by pulp and sawmill industries. However, according to DAFF, the volume of roundwood purchased by these industries (Table 10 and Table 11 in the appendix) was greater than the level of wood consumption for these same industries estimated by this study (Table 3). DAFF did not report roundwood purchases by the wooden panel industry, but reported the production of semifinished wooden panels in the country. It is not clear if pulp and sawmill industries supplied wood resources for manufacturing wooden panels in South Africa. Nevertheless, the pulp and wooden panel industries demanded the same wood chips for manufacturing its semifinished wood products.

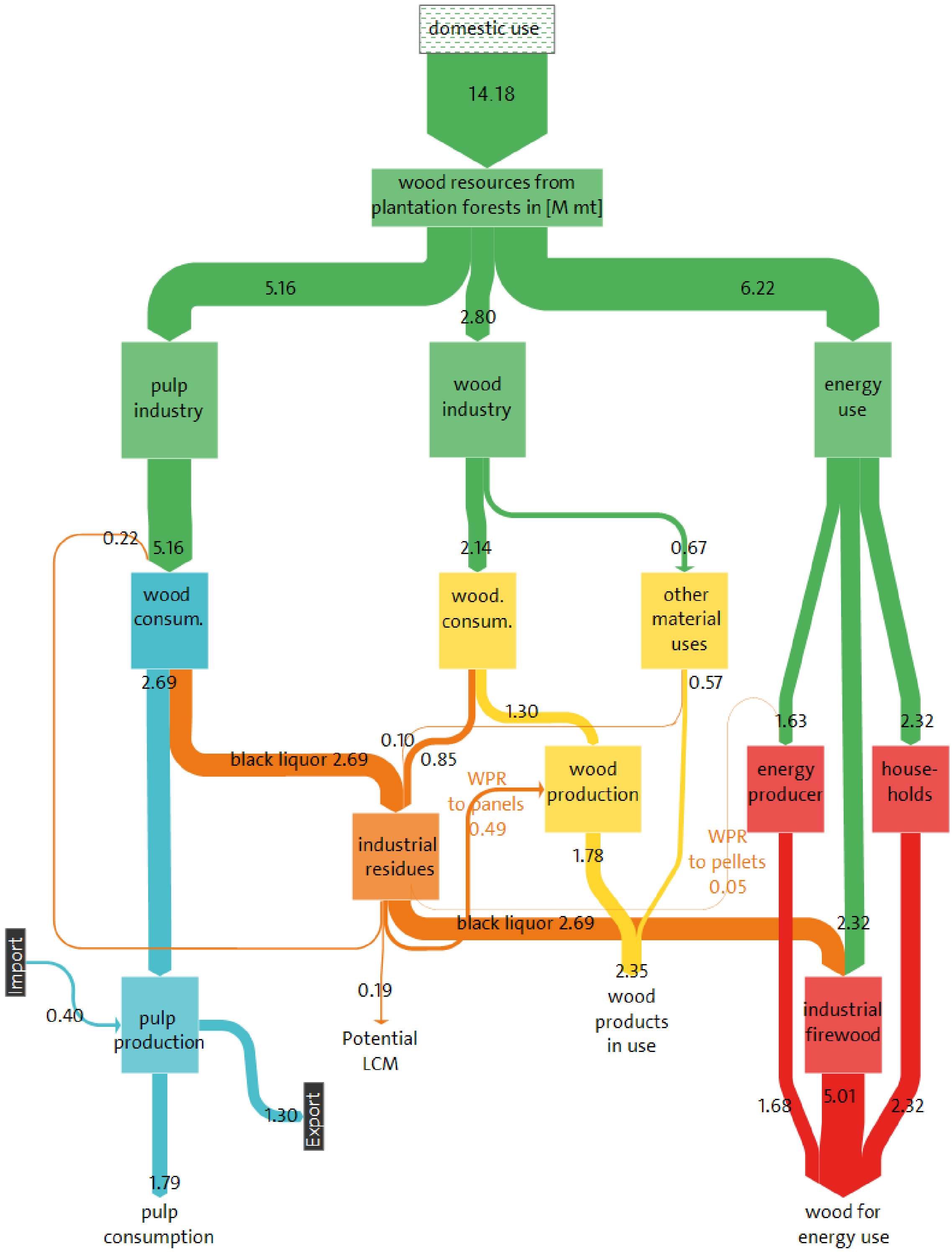
The estimated wood consumption for manufacturing wooden poles and mining timber (Other material uses) by this study was similar to the DAFF-reported volume of roundwood purchased by these same industries. However, according to DAFF, the volume of roundwood purchased for manufacturing wood veneer (Table 10 in the appendix) was quite a bit lower than the wood consumption for this same industry estimated by this study. This fact may be explained by a seasonal purchase of wood or by the existence of a stock of wood by the veneer and plywood industries. However, there is no clear evidence to prove this hypothesis. Otherwise, it is not clear if the reported volume of semifinished plywood panel was exclusively manufactured with plantation forest resources.

The most challenging step of calculating the wood resource balance was the estimation of wood consumption for energy use. According to the literature, roundwood consumption for energy in the SSA region is two to three times higher than in any other region of the world (Jin et al., 2017). However, a study on biomass energy dependence in South Africa indicated that wood is not the most frequently used energy source for households and represented less than 10 % of the energy sources for this segment (Muazu et al., 2020). Wood consumption for energy use is hard to assess, because in many cases, harvested or collected wood is utilized without being commercialized. Therefore, a certain volume of wood for energy use is not reported in production or sales statistics.

This study preferred to carry out the wood resource balance calculation considering the annual consumption of wood fuel reported by FAO instead of the volume informed by DAFF. According to FAO, the reported volume of wood fuel produced in South Africa in 2018 did not make a distinction between firewood sourced by plantation or indigenous forests. The industrial firewood segment figures represented the greatest demand for wood for energy use. However, the most relevant source of secondary wood resources was considered to be solid wood fuel, which was manufactured with primary wood resources and then further dedicated for energy use.

If plantation and indigenous forests supplied primary wood resources for the wood-based industry in South Africa, the volume of secondary wood resources also contains both types of forest. The most relevant secondary wood resource in South Africa is in fact a WPR, so-called black liquor. Alongside black liquor, South Africa had available solid WPR as sawmill byproducts and wood chips. Both liquid and solid WPR are important sources of energy in South Africa, and the growing demand for renewable energy places increasing pressure on forests (Dovey, 2009). Especially the production of wood pellets utilizing solid WPR as sawmill byproducts played an import role in the country. Despite efforts to establish a resilient national wood pellet industry in South Africa, the region has faced challenges in developing this market (Bowd et al., 2018).

In addition to energy use, solid WPR are in worldwide demand by the livestock industry as poultry bedding (Kriel, 2020). The South African Poultry Association (SAPoultry) mentioned that pine shavings and sawdust are the most preferred material, but limited in supply and expensive in some areas of the country. No mention of WPR volume dedicated for this purpose was reported. Three interviewed sawmills declared that the destination of solid WPR depends on the higher price paid for it. The results of the resource balance presented in volumes were converted into mass, to design an MFA for wood resources. The WFA illustrates that WPR in South Africa are almost completely utilized for further uses, as presented by the arrow labelled Potential LCM in Figure 19.



Notes: Volumes in millions of metric tons [M mt]; WPR = wood processing residues; LCM = lignocellulosic materials. Arrows in green indicate primary wood resources; orange represents secondary wood resources; yellow and blue figure semifinished wood products; red comprises wood resource flows destined to energy use

Figure 19 – Wood-flow-analysis for plantation forests in South Africa in 2018

Estimating the volume of available WPR in South Africa proves to be difficult, given the lack of accurate data. First, there are discrepancies between the volumes reported by DAFF and FAO regarding semifinished wood products. Even if the utilized conversion factors have been informed by official sources in South Africa, there may be inconsistencies in these values. For instance, another estimate of the available amount of sawmill byproducts in South Africa by the BEA study reported a volume of 0.95 M mt in 2015 (Hugo, 2016). According to the BEA study, this volume included bark and did not consider that pulp industry had consumed WPR. Additionally, this estimation did not take the production of wooden panels and wood pellets into consideration. Therefore, it is assumed that the volume reported by the BEA is an overestimation.

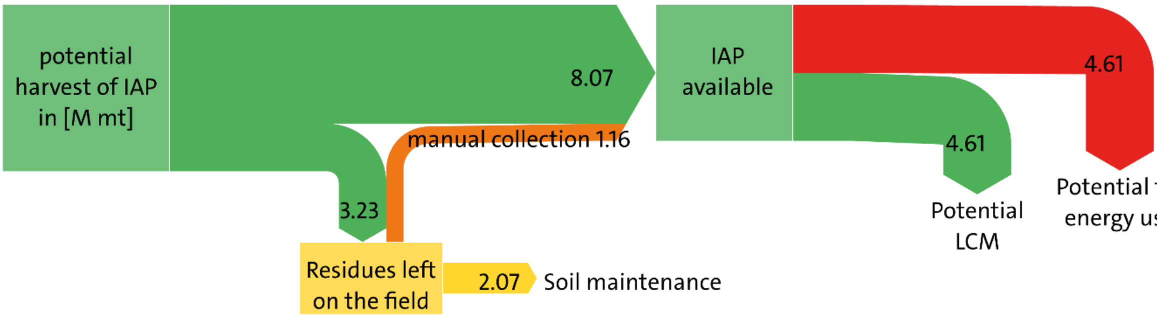
Despite the many limitations of BEA and this present study, the estimated volumes of WPR represent a source of LCM for manufacturing alternative building materials. The volume of WPR found to be available by both studies is seasonal and dependent on wood-based industry consumption and production behavior. Knowing that South Africa intends to adopt clean energies based on renewable resources, the price and availability of wood resources could vary in the coming years (Dovey, 2009). Given the rapid urbanization situation, fuelwood obtained informally will remain an important source of energy for households in poor regions inside South Africa (Guild & Shackleton, 2018). This study holds that policy is a key factor in bringing South Africa closer to a higher rate of cascading use of wood, respecting its population needs. In addition, a better overview of the importance of indigenous forests in the supply of wood in South Africa is necessary. This information is essential to assist governments in regulation of the wood market and in approximating the circular economy concept.

4.1.2 Invasive alien plant flow analysis

The proliferation of IAP and their effects on biodiversity are harmful (Kraaij et al., 2017; Richardson et al., 2020; Rouget et al., 2015). The most effective solution to alleviating environmental issues relating to IAPs is biological control via harvesting operations (National Environmental Management: Biodiversity Act (10/2004): Draft Alien and Invasive Species Lists, 2014; Rouget et al., 2015). As already mentioned by the BEA study, invasive plants are a significant source of LCM and an attractive source of renewable energy for South Africa (Hugo, 2015). Therefore, the raw material category of invasive alien plant flows assessed the volume of primary LCM obtained via the harvest of invaded areas in this country.

According to the BEA study, a 20-year period of regular IAP harvesting operations would result in an estimated volume of 11.3 million mt [M mt] LCM available annually (Hugo, 2016). The same study considered that only 71 % of this total harvestable volume would be readily available for further uses (Hugo, 2016). The leftover volume refers to harvest residues, which remain on the fields. If manual collecting of harvest residues occurs, an additional volume of LCM can be obtained. The BEA study estimates that at least 36 % of the total harvest residues left on the fields can be collected manually.

Contrary to the objectives of this study, the BEA study aimed to seek out renewable energy sources. This means that the total estimated volume of IAP harvested by BEA was exclusively dedicated to energy use. The present study, though, was dedicated to estimating the availability of LCM for material uses. As mentioned in the Materials and Methods chapter, half of the potential LCM volume obtained by IAP harvesting operations was destined for energy use and the other half was considered to be available for material uses. The MFA for the raw material category Invasive alien plant flows was designed in the e!Sankey software and is presented in Figure 20.



Notes: Volumes in millions of metric tons [M mt]; LCM = lignocellulosic materials.

Arrows in green indicate primary lignocellulosic resources; orange represents secondary lignocellulosic resources; yellow shows final uses; and red comprises LCM flows destined for energy use

Figure 20 – Material flow analysis of harvestable volume of invasive alien plants in South Africa in 2018

The MFA of harvestable volume of IAP in South Africa in 2018 could have supplied 4.61 M mt of LCM for manufacturing bio-based building materials. Another 4.61 M mt of LCM could have supplied the inland energy demand. It is important to mention that this estimated volume of LCM from the harvesting of IAP is only available if the biological controls proposed by the South African government are indeed performed. However, the majority of the invaded areas in the country are privately owned (L. Henderson, 2007; Nkambule et al., 2017). Additionally, biological control represents costs relative to harvesting operations, including equipment and a skilled workforce (Nkambule et al., 2017). These economic factors can of course restrain or hinder the biological control of IAP. These facts are indicative of the estimated volume of LCM from IAP harvest possibly being lower in reality.

Nevertheless, there are enough reasons to believe that invasive species will be harvested and brought under control. IAP have changed the landscape, hindering endemic species from propagating and worsening the issue of water scarcity in South Africa (Nkambule et al., 2017; van Wilgen & Wilson, 2018). Therefore, the biological control of IAP is essential to maintain and save the water balance. Moreover, the benefits of IAP management were observed on grazing growth and production improvement in agricultural crops (Nkambule et al., 2017). There is no doubt about the advantages of IAP biological control: consequently, it is in the interest of the government, ranchers and farmers to take steps to control IAP.

This study is of the position that policies are a key factor to stimulating IAP harvest operations. South African alien plants are additionally growing in importance in the field pharmacology for the production of antibiotics (Maema et al., 2019; Omokhua et al., 2018; Omokhua et al., 2019). Further, IAP harvesting represents a relevant source of LCM for energy use (Hugo, 2015, 2016) and for the manufacturing of bio-based building materials in South Africa. IAP harvest can thus supplement the production of value-added products (Nkambule et al., 2017), a factor which generates income. Even though the LCM analyzed in this raw materials category are primary resources, obtaining them is beneficial to the environment.

4.1.3 Agricultural crop flow analysis

Agricultural crops are a significant source of LCM in South Africa (Hugo, 2016). Therefore, the agricultural crop flow category investigated the volume of secondary LCM from the harvest and processing of selected field crops in South Africa in 2018. The field crops selection was defined in Materials and methods according to the agricultural profile reported for South Africa by DAFF. The estimation of secondary LCM available in South Africa is presented in Table 5.

Table 5 – Volume of byproducts from agricultural field crops in South Africa

Agricultural field crops		**Residues**	**Soil maintenance**	**Animal feed**	**Availability**
	Volume in	[mt]			
Grains & cereals	Maize	9,696,942	4,848,471	3,393,930	1,454,541
	Wheat	874,950	437,475	306,233	131,243
	Sorghum	65,550	32,775	22,943	9,833
	Barley	168,850	84,425	59,098	25,328
	Oats */2017*	60,488	30,244	21,171	9,073
Oil seeds	Soybean	770,000	385,000	269,500	115,500
	Sunflower seed	431,000	215,500	150,850	64,650
	Canola/rapeseed	46,750	23,375	16,363	7,013
	Groundnut	46,170	23,085	16,160	6,926
OC	Sugarcane */2017*	2,863,129	1,431,565	1,002,095	429,469
	Sugarcane bagasse */2017*	773,045	386,522	0	386,522
Σ	**Total**	**15,796,874**	**7,898,437**	**5,258,343**	**2,640,098**

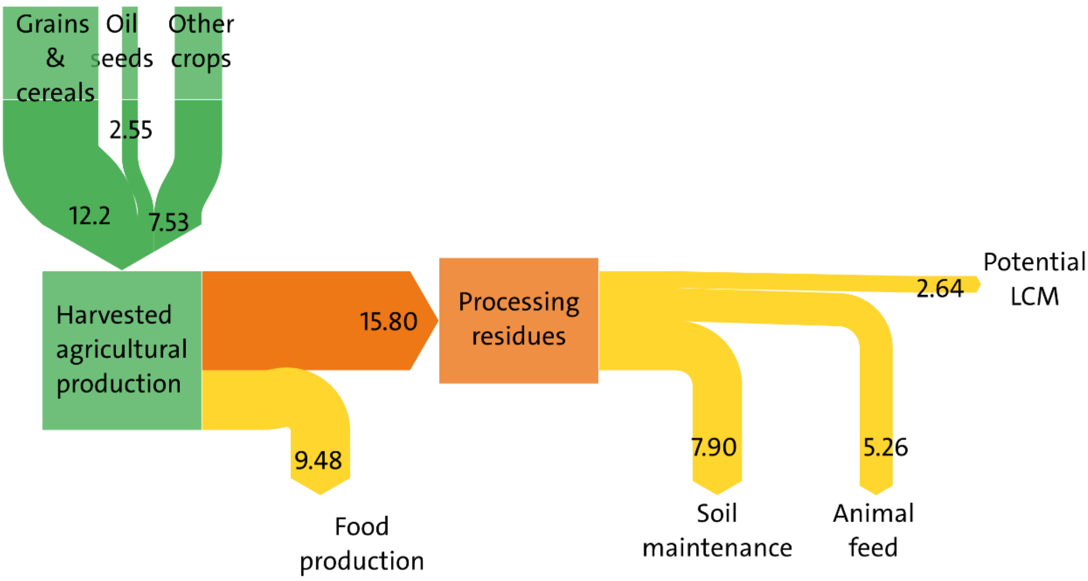
Notes: [mt] = metric tons; OC = other crops

Agricultural crop production in South Africa is in great part represented by grains and cereals, of which maize figured as the most produced grain. Maize crops are also the most representative source of agricultural residues and supplied around 1.4 M mt of LCM in 2018. The other crops classified as grains and cereals investigated in this study were wheat, sorghum, malting barley, and oats. Together, these crops supplied another 175 thousand mt of LCM in 2018.

Wheat and barley are grasses cultivated extensively for their seeds which assure food security across the globe (Luhar et al., 2019). This fact indicates a constant supply of this type of agricultural byproduct. Straw is the usual agricultural byproduct occurring in the harvest and processing of wheat and barley crops. In contrast to wheat and barley straw, sorghum crops supply another type of agricultural residue, called sorghum bagasse. Sorghum was appointed in fewer studies as agro-filler suitable for manufacturing bio-based composites (Motaung & Linganiso, 2018). Even if in lower proportions, oil seed field crops supplied agricultural byproducts as well, especially soybeans and sunflower seeds. All oil seeds together occupied 15 % of the total area for crop production in South Africa (DAFF, 2019). Together, these crops supplied 194,000 mt of agricultural byproducts in 2018. Additionally, recent research has pointed out the potential of soybean-based adhesives for plywood manufacture (Buddi et al., 2015; Buddi et al., 2018).

Another relevant source of agricultural residues in South Africa is sugarcane bagasse, which represented the second biggest source of secondary LCM from agricultural crops in 2018. Sugarcane is largely cultivated on flat land (Motaung & Linganiso, 2018) and covered 3.1 % of the total area for crop production in South Africa in 2018 (DAFF, 2019). However, sugarcane crops experienced a production decline from 15.7 to 7.5 M mt between 2007 and 2017 (Stats SA, 2017). Traditionally, on a global scale, the sugar industry generates electricity using bagasse in cogeneration systems, and recent research has noted that pellet production based on sugarcane bagasse had improved not only its energy content but has also facilitated transportation (Khoodaruth, 2014; Mohlala et al., 2016). Even if alternatives to avoid the incorrect disposal of sugarcane bagasse are known (Olayiwola et al., 2021), this type of secondary LCM is mostly landfilled in South Africa (DEA, 2018).

Bagasse ash is rich in silica (Si) and aluminum (Al), valuable for cement and concrete production (Payá et al., 2002). As already mentioned, the controlled burning of agricultural byproducts is a source of active pozzolans able to be utilized as a filler for asphalt and concrete, and for building insulation (He et al., 2020). Consequently, all the investigated agricultural byproducts in this study are potential LCM for manufacturing bio-based building materials in South Africa. The estimated volume of byproducts from agricultural crops in this study reached 2.6 M mt in 2018. The MFA for this raw material category was built on e!Sankey and is presented in Figure 21.



Notes: Volumes in millions of metric tons [M mt]; LCM = lignocellulosic materials. Arrows in green indicate primary lignocellulosic resources; orange represents secondary lignocellulosic resources; yellow shows final uses.

Figure 21 – Material flow analysis from selected agricultural field crops in South Africa in 2018

Fruit tree crops such as orange and apple orchards represented 1.3 % of the total area dedicated to agriculture in South Africa. Additionally, the replacement of old trees by younger ones could have been a source of LCM. However, three interviewed fruit producers confirmed that replaced trees are entirely chipped into smaller particles and utilized as mulch for the orchards. This process occurs near the orchard crops, decreasing logistical costs.

The MFA of agricultural residues in this study confirmed that field crops are a relevant source of LCM for manufacturing bio-based building materials in South Africa. Another estimate of the available volume of agricultural residues in South Africa was reported by the BEA study. In addition to the agricultural crops investigated by this study, the BEA study also considered the production of dry beans, chicory, and cotton in their calculations. Consequently, the BEA study reported higher volumes of agricultural residues available annually in South Africa, of up to 5.8 M mt (Hugo, 2016). There is a clear discrepancy between the LCM volumes estimated by this study and by the BEA study. This discrepancy is explained due to the different values utilized by each study.

The BEA study was conducted in 2014, and since then, the composition of agricultural crops has changed in South Africa. For instance, maize crops covered 3.1 million hectares in 2014; four years later the same crop occupied only 2.5 million hectares (DAFF, 2019; Stats SA, 2017). Tending in the opposite direction, soybean crops gained space in the country and covered at least 100,000 hectares more in 2018 than in 2014 (DAFF, 2019; Stats SA, 2017). Considering that the processing of maize and soybean crops results in 74 % and 50 % of byproducts, respectively, the LCM volume estimated by BEA in 2014 tends to be higher, if the maize crop area was larger in this year.

In fact, the results obtained by this study may be an underestimate, as not all agricultural crops available in South Africa were taken into consideration. The conversion factors used were also published more than ten years ago and may be out of date. Still, the volume of agricultural byproducts represents a substantial source of LCM annually available in South Africa, and this study concludes that only government policy is able to stimulate the reuse and controlled burning of agricultural byproducts instead of their disposal. The challenges of improving the cascading use of LCM in the country remain. However, there are no doubts that agricultural crops in South Africa do figure as a relevant source of raw material for manufacturing bio-based composites.

4.1.4 Recyclable flow analysis

Large portions of material disposed after their end-of-life were landfilled in South Africa in 2018 (DEA, 2018). Indeed, not all types of disposed-of materials are recyclable, but they are reusable. The Recyclable flows raw material category investigated this waste generation and its composition in South Africa with the aim of identifying suitable resources for construction. This study focused specifically on the identification of suitable resources for manufacturing WPC and geopolymer composites. Therefore, this raw material category investigates only the volumes of plastics waste and earthen-based processing residues (e.g., bottom and fly ash, slag). Table 6 shows the volume of selected types of waste available for recycling and/or reuse in South Africa in 2018.

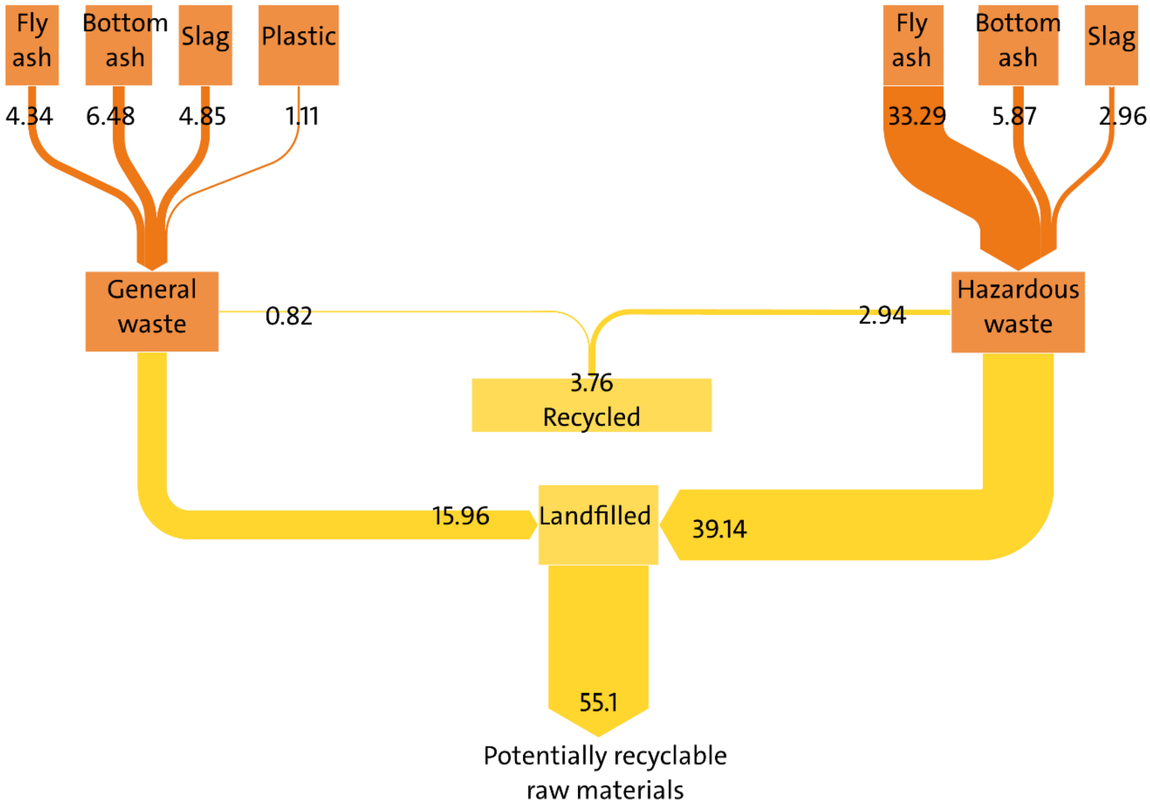
Table 6 – Waste generation of types selected for this study and their available volumes for recycling or reuse in South Africa in 2018

<table>
<tr><th colspan="2" rowspan="2">Waste type</th><th>Weight</th><th>Import</th><th>Export</th><th>Recycled</th><th>Available for recycle/reuse</th></tr>
<tr><th colspan="5">[mt]</th></tr>
<tr><td rowspan="4">General</td><td>Plastics</td><td>1,113,362</td><td>6,748</td><td>20,856</td><td>480,374</td><td>618,880</td></tr>
<tr><td>Fly ash (inclusive dust)</td><td>4,346,080</td><td>NA</td><td>NA</td><td>134,728</td><td>4,211,352</td></tr>
<tr><td>Bottom ash</td><td>6,489,080</td><td>NA</td><td>NA</td><td>201,161</td><td>6,287,919</td></tr>
<tr><td>Slag</td><td>4,859,025</td><td>NA</td><td>NA</td><td>0</td><td>4,859,025</td></tr>
<tr><td colspan="2">Total general waste</td><td>16,807,547</td><td>6,784</td><td>20,856</td><td>816,264</td><td>15,977,175</td></tr>
<tr><td rowspan="3">Hazardous</td><td>Fly ash (inclusive dust)</td><td>33,290,115</td><td>NA</td><td>5,000</td><td>2,329,958</td><td>30,955,175</td></tr>
<tr><td>Bottom ash</td><td>5,874,726</td><td>50</td><td>NA</td><td>411,234</td><td>5,463,542</td></tr>
<tr><td>Slag</td><td>2,923,640</td><td>1,750</td><td>NA</td><td>204,777</td><td>2,720,613</td></tr>
<tr><td colspan="2">Total hazardous waste</td><td>42,088,481</td><td>1,800</td><td>5,000</td><td>2,945,970</td><td>39,139,311</td></tr>
<tr><td colspan="2">Total waste</td><td>58,896,028</td><td>8,548</td><td>25,856</td><td>3,762,234</td><td>55,116,486</td></tr>
</table>

Notes: NA = not available; [mt] = metric ton

Source: State of Waste Report (SoWR) by Department of Environmental Affairs (DEA) (DEA, 2018)

In 2018, the generation of general waste in South Africa supplied approximately 18 million mt [M mt] of resources able to be recycled or reused for the local manufacture of building materials. If the volume of hazardous waste is taken into consideration as well, the total volume of resources that could be recycled or reused reached 55 M mt in 2018. The MFA for this raw material category was designed using e!Sankey and is presented in Figure 22. Volumes of waste imported and exported are not shown in the MFA because their volumes are too small compared with the other input and output flows. For traded volumes of waste, see Table 6.



Notes: Volumes in millions of metric tons [M mt]. Arrows in orange represent secondary resources and arrows in yellow, resources' final destinations.

Figure 22 – Material flows analysis from selected types of waste in South Africa in 2018

South Africa relies on coal for electricity generation and therefore produces great volumes of fly and bottom ash. The DEA estimated a total volume of 37.6 M mt of fly ash and 12.4 M mt of bottom ash available in South Africa in 2018 (DEA, 2018). However, this total ash volume is comprised of both general and hazardous waste, and unfortunately, more than 90 % of this ash was landfilled in the country that same year (DEA, 2018). It remains apparent that these available earth-based materials are suitable resources for manufacturing geopolymer composites (Asante et al., 2021; Emdadi et al., 2017; Sá Ribeiro et al., 2016). However, hazardous fly and bottom ash contain heavy metals, and these substances contaminate the environment via leaching (Kurda et al., 2018). Therefore, further research on the composition of these types of waste is recommended before its utilization as a raw material for geopolymers. Even if only the general waste volume of fly and bottom ash figures as a suitable raw material for construction, though, South Africa still has a great potential for the local development of geopolymer-based composites.

According to DEA, South Africa generated a type of waste called slag that combined to total a volume of 7.8 M mt in 2018 (DEA, 2012, 2018). This total volume included general and hazardous slag, and its composition therefore needs to be further investigated before it can be utilized as a raw material for construction. Still, slag is a suitable resource for manufacturing geopolymer composites (Duxson et al., 2007). A well-established market able to access sources of blast furnace slag is however appointed as a barrier to the development of geopolymers (van Deventer et al., 2012). Regardless, even if only the general waste volume of slag figures as a suitable raw material for geopolymer manufacture, South Africa still has great potential to supply this resource. Currently, South African companies do reuse a certain quantity of ash for brickmaking and mine backfilling, a usual process within the mining industry in which an excavated hole is refilled (FLYABILITY SA). Actually, neither ash nor slag has achieved a satisfactory recycling rate: both stand at less than 10 % (Table 25 in the appendix).

The volume of plastic materials disposed of in South Africa was visibly smaller than the volume of ash and slag. However, nearly 1.1 M mt of plastic materials waste was generated in the country in 2018 (DEA, 2018). According to DEA, 43.7 % of the disposed-of volume of plastic was recycled (Table 25). In 2018, South African plastic producers converted 1,876,250 mt of polymer into products; a share of 18 % (332,249 mt) of this total volume was represented by recycled plastics (Plastics SA, 2018). At least 40 % of the plastic products manufactured in the country are utilized for durable applications such as sewage pipes, automotive components, landfill liners, laminate flooring, and so on; therefore, these are not available for recycling within a 20-year timeframe (DEA, 2018; Plastics SA, 2018). The most oft-recycled materials were PE packaging films. From the total volume of plastics available for recycling, a great part was demanded by recyclers for further uses (Plastics SA, 2019). Not all recovered volume was transformed into recycled plastic because of processing losses, however, and ultimately 313,780 mt (17 %) were effectively turned into new products. The recycled volume of plastic reported by Plastics SA is lower than the volume reported by the DEA. This fact can easily be explained: Plastics SA is a voluntary organization of plastic producers and therefore does not have access to information from all of the producers in the country. The company Plastics SA still represents the majority of producers, however, and affirmed that the lack of infrastructure for the collection and management of waste in South Africa obstructs the increase of plastic recycling rates (Plastics SA, 2018). Indeed, recycling rates will only increase if industries also commit to increased levels of recycled content in their products (Plastics SA, 2019).

The volume of other suitable secondary resources for bio-based building materials, likely wood from sources other than forest, was reported by DEA on the SoWR. DEA estimated that approximately 18.3 % of the total waste generated in South Africa was represented by garden waste. This type of organic waste occurs during pruning of urban forests (e.g., branches, grass, and leaves from parks) and summed 4.2 M mt of LCM (DEA, 2018). However, this volume of LCM was reported to have been used as mulch and landfill cover material (DEA, 2018) and was therefore disregarded in this study. Another waste type, which falls under the category of construction and demolition, is partially represented by the volume of demolition wood (2.7 %) and by plastics (1.1 %) (DEA, 2018). This type of waste was however also utilized as cover material in landfills (DEA, 2012, 2018; Stats SA, 2020), and for this reason not accounted for as a source of raw materials for manufacturing bio-based composites in South Africa.

The further development of recycling structures would very obviously facilitate the collection and separation of local waste materials. Additionally, reports on waste streams have noted that innovation and the development of new technologies to transform waste into value-added products are an important step toward achieve sustainability within the country (DEA, 2018; Plastics SA, 2018), and as mentioned, this study holds that adjusted polices are a key factor to stimulating the valorization of waste into value-added products. The engagement of government institutions, industries, and communities is necessary for the development of sustainable strategies and to avoid waste generation. Furthermore, recycling and reusing waste is an opportunity for South Africa to set down a path forward and adapt into circular economies (Duxson et al., 2007; Emdadi et al., 2017; Gupta, 2017; Youssef et al., 2019). On this path, this region would move closer to the concept of sustainability (Stegmann et al., 2020), establish jobs for local communities (ILO, 2015; UNEP et al., 2008), and move towards a fairer and healthier society.

5 CONCLUSIONS

The lack of housing in South Africa increased significantly through the rapid urbanization. This development aggravated already poor waste management and has negatively affected the local environment. These developments notwithstanding, South Africa disposes of many resources in landfills after their end-of-life. Additionally, the country imports building materials instead of utilizing local resources for construction. Knowing this, this study has aimed to investigate how much of certain renewable and secondary resources were available in the country.

South Africa periodically carried out surveys to monitor various sources of raw materials and their consumption patterns. However, there is a discrepancy between information published by more than one source. Further limitations of this study are due to the deficits and outdated conversion factors essentials to estimate consumption volumes of each studied raw material. Even with limited information, this study designed four different material flow analysis (MFA) for pre-established raw material categories (see section 3.1) to enable a concrete discussion about availability of renewable and secondary resources for construction in South Africa in 2018. Therefore, this study contributes with information to support the cascading use of resources and development circular economy outside European boarders.

The investigation focused on renewable and secondary resources suitable for manufacturing a selection of BBC: thermoplastic and geopolymer composites. In South Africa LCM were sourced by forests, via eradication of invasive alien plants (IAP) and through the processing of agricultural crops. All these sources together supplied 7.4 million metric tons [M mt] of this type of renewable resource in 2018. The most attractive LCM source was created by the eradication of IAP, which accounted for 62 % of the total volume of LCM available in the country in 2018. In fact, this type of LCM is a primary resource, but its harvest benefits other environmental aspects, such as water balance and biodiversity security.

Furthermore, agricultural crops were the second most relevant source of LCM in South Africa and provided 35.5 % of the total volume of renewables investigated in this study. The volume of LCM provided by agriculture is in fact a secondary resource, called byproducts, and its utilization is highly indicated to benefit the cascade use of raw materials. However, agricultural byproducts are already demanded for livestock feed and soil maintenance. It is recommended that this existing demand is respected, and that only the residual volume of LCM is allocated to provide raw materials for manufacturing BBC in South Africa. Forests accounted for only 2.5 % of the total volume of LCM available in South Africa in 2018. This raw material category investigated the volume of secondary resources obtained from the forest and wood-based industry, called wood processing residues (WPR). The WPR figured as the least representative source of LCM, as they are demanded for other material and energy uses in the country (e.g. for wooden panel production, eventually animal bedding and/or wood pellets). Even so, the residual volume of WPR figures as an important source of LCM in South Africa and its utilization is beneficial to improve the cascading use of renewable resources.

In addition, this study investigated South Africa's waste generation and its composition to estimate the available volume of plastic, ash, and slag. These materials were selected because they are suitable to be reutilized for manufacturing thermoplastic and geopolymer composites. At least 54.5 M mt of ash and slag were available in the country in 2018. However, 72 % of this total volume is considered to be hazardous waste and must be analyzed or possible treated before its utilization. Nevertheless, if only the non-hazardous volume of ash and slag is considered, South Africa still had more than 12 M mt of this type of raw material. This fact indicates a great potential to establish a geopolymer composite manufacturing in the country. The volume of recyclable plastic materials in the country was much smaller and accounted for only 620,000 mt in 2018. However, South Africa already recycled a great part of plastics disposed as waste (43.7 %; see Table 6). If both volumes, recycled and recyclable plastics are accounted for, the country had the opportunity to reuse around one million mt of this type of raw material in 2018.

The main limitation of this study was the lack of coherent and updated data. Furthermore, possibly obsolete conversion factors for South Africa may mask the reality and make it difficult to estimate potential resource availability. In fact, building materials made from renewable and secondary resources are appointed as an alternative to alleviate resource scarcity. However, this study did not consider economic aspects related to the costs of collection, separation and recycling to reuse the investigated resources. Even so, this study found that South Africa had enough local raw material to develop more sustainable housing.

In fact, the lack of data impeders the development of econometric modelling. Nevertheless, the potentially lower cost of secondary materials when compared with the primary ones is an interesting aspect for South Africa to consider. The greater the demand for resources, the higher their price; therefore, the reuse of resources has the potential to mitigate raw material scarcity and abusive prices.

In addition to an economic feasibility analysis, this study recommends conducting a life cycle assessment (LCA) of thermoplastic and geopolymer composites. Carrying out an LCA during the development phase of these building materials ensures that the resources utilized to manufacture them are sustainably sourced. In addition to an economic feasibility analysis and an LCA, other investigations are essential to combine good waste management practices with economic and social gains. For example, the analysis of the effects that BBC manufacturing has on local communities and the creation of green jobs should be considered. Nevertheless, this study concludes that polices are needed to improve cascading use of materials and develop local manufacturing of bio-based building materials in the country. Achieving economic, environmental and social development is an important task for governments, industries and communities. Finally, this study concludes that monitoring renewable and recyclable resources and developing techniques to collect, store and classify waste materials are the first steps towards developing circular economies in and outside South Africa.

APPENDIX

1. Introduction | Urbanization in South Africa

Source: Google Maps

Figure 23 – Informal dwellings in Stellenbosch (Kayamandi) popularly called ‘shacks’ or ‘shanties’

Source: Google Maps

Figure 24 – Formal dwellings in Stellenbosch (Kayamandi) provided by government via the Reconstruction and Development Programme (RDP)

RDP houses in Stellenbosch

Internal walls of RDP houses

Internal walls of an RDP house attacked by mold

Source: BioHome Project. Photos by Tenele Dlamini

Figure 25 – Formal dwellings in Stellenbosch (Kayamandi) provided by government via the Reconstruction and Development Programme (RDP) and its internal conditions

2. State of the art | Monitoring renewable and secondary resources

Table 7 – Land cover in South Africa

Land cover	**Area** [ha]	**Share** [%]
Savanna *(Woodland, Low shrubland)*	37,300,700	30.6
Grassland	25,872,300	21.2
Herbaceous crops *(Woodland open bush)*	12,460,400	10.2
Albany Thicket *(Thicket Dense bush)*	8,290,500	6.8
Fynbos *(Shrubland fynbos)*	5,327,410	4.4
Forest *(Indigenous Forest)*	428,290	0.4
Plantation forest	1,191,638	1.0
Others	31,107,762	25.5
Total land area	**121,909,000**	**100**

Source: Food and Agriculture Organization (FAO); Department of Agriculture, Forestry and Fisheries (DAFF); Statistics South Africa (DAFF, 2018; FAO, 2020; Stats SA, 2017)

Table 8 – Land use in South Africa

Land use	**Area** [ha]	**Share** [%]
Livestock *(Grazing land)*	36,536,940	30.0
Agriculture	7,614,392	6.2
Urban area	2,096,933	1.7
Plantation forest	1,191,638	1.0
Protected and conservation areas	19,092,484	15.7
Others	55,376,613	45.4
Total land area	**121,909,000**	**100**

Source: Department of Agriculture, Forestry and Fisheries (DAFF); Statistics South Africa; BioEnergy Atlas for South Africa; Forestry South Africa (FSA) (DAFF, 2018, 2019, 2020; Godsmark & Oberholzer, 2019; Hugo, 2016; Stats SA, 2017)

3. Materials and methods | Forestry flows

Table 9 – Production volume of semifinished products in South Africa in 2018

Semifinished wood products by species	Softwood	Hardwood	Total
Volume in	[m³]		
∑ Sawnwood	**2,115,940**	**101,838**	**2,217,778**
• For building products	1,458,221	32,085	
• For furniture products	70,676	10,943	
• For other products	587,043	58,810	
∑ Wooden poles	**111,481**	**307,178**	**481,659**
• Transmission poles	7,439	192,646	
• Telephone poles	1,482	10,591	
• Other poles	102,560	166,941	
Veneer	**24,145**	NA	**24,145**
Plywood	**16,016**	NA	**16,016**
∑ Wooden panels	NA	NA	**1,426,434**
• Particle boards			1,015,031
• Fiberboards (MDF/HDF)			411,403
Volume in	[mt]		
Mining timber	NA	**327,456**	**327,456**
∑ Wood processing residues	**863,507**	**1,654,446**	**2,519,953**
• Wood chips	305,092	1,565,242	
• Sawmill by-products	558,415	89,204	
Charcoal	NA	**55,655**	**55,665**
Firewood	**5,653**	**9,143**	**14,796**

Notes: MDF = medium density fiberboard; HDF = high density fiberboard; NA = not available; [m³] = cubic meter; [mt] = metric ton

Source: Department of Agriculture, Forestry and Fisheries (DAFF) (DAFF, 2018)

Table 10 – Roundwood species purchased for final use in sawmill, veneer, wooden poles, charcoal and firewood in South Africa in 2018

Final use	Sawmill	Veneer	Wooden poles	Charcoal and firewood	
Species	[m³]			[mt]	[m³]
SW	4,249,165	2,985	115,796	NA	NA
E. grandis	524,145	NA	218,664	1,310	1,926
Other gum	17,650	NA	9,000	25,157	31,446
Wattle	NA	NA	NA	57,625	65,577
Other HW	NA	NA	9,486	NA	NA
Total	**4,790,960**	**2,985**	**352,946**	**84,092**	**98,949**

Notes: SW = Softwood; HW = Hardwood; NA = not available; [m³] = cubic meter; [mt] = metric ton

Source: Department of Agriculture, Forestry and Fisheries (DAFF) (DAFF, 2018)

Table 11 – Roundwood species purchased for final use as mining timber and wood pulp in South Africa in 2018

Final use	**Mining timber**		**Wood pulp**	
Species	[mt]	[m³]	[mt]	[m³]
SW	43,931	43,931	1,451,189	1,451,189
E. grandis	305,762	449,470	1,322,317	1,943,806
Other gum	29,438	36,798	5,592,181	6,990,226
Wattle	NA	NA	1,276,472	1,452,625
Other HW	NA	NA	10,929	13,661
Total	**379,131**	**530,199**	**9,653,088**	**11,851,507**

Notes: SW = Softwood; HW = Hardwood; NA = not available; [m³] = cubic meter; [mt] = metric ton

Source: Department of Agriculture, Forestry and Fisheries (DAFF) (DAFF, 2018)

Table 12 – Sales of semifinished wood products from plantation forests in South Africa in 2018

Semifinished wood products	**Sawnwood/ Veneer**	**Wooden poles**	**Mining timber**	**Wood pulp**	**Charcoal and firewood**	**Other products**
Species	[m³]		[mt]			
SW	5,195,396	52,011	NA	2,741,735	25,294	56,517
E. grandis	98,352	205,237	304,996	3,170,315	50,485	7,621
Other gum	15,830	32,439	47,188	3,153,419	18,274	6,909
Wattle	NA	21,312	NA	711,458	84,063	11,055
Other HW	152	21,840	NA	23,922	648	99
Total	**5,309,730**	**332,839**	**352,184**	**9,800,849**	**178,764**	**82,201**

Notes: SW = Softwood; HW = Hardwood; NA = not available; [m³] = cubic meter; [mt] = metric ton

Source: Department of Agriculture, Forestry and Fisheries (DAFF) (DAFF, 2018)

Table 13 – Production and sales of wood pulp in South Africa in 2018

Production volumes by wood pulp type	**[mt]**	
∑ Wood pulp	**1,798,229**	**1,938,000**
• Mechanical	224,653	86,000
• Semi-chemical	161,523	189,000
• Chemical	372,580	667,000
• Dissolving	1,039,473	996,000

Source: Department of Agriculture, Forestry and Fisheries (DAFF) (DAFF, 2018) and underlined values figured the volume of virgin pulp production in South Africa in 2019 (air-dry weight, with 10% moisture content), reported by Paper Manufacturers Association of South Africa (PAMSA) (PAMSA, 2018)

Table 14 – Production of timber products in South Africa in 2018

Semifinished wood products	**Production**		
Species	SW	HW	∑
Volume in	[m³]		
Sawnwood	2,003,068	87,000	**2,090,068**
Veneer	20,000	NA	**20,000**
Plywood			**87,000**
∑ Wooden panels			**1,295,031**
• Particle boards			1,015,031
• Fiberboards (MDF/HDF)			280,000
Wood chips and particles [1]			**1,938,466**
Wood residues [2]			**526,234**
Wood fuel [3]	25,764	12,000,000	**12,025,764**
Volume in	[mt]		
∑ Wood pulp			**3,013,000**
• Mech. & semi-chemical			315,000
• Chemical			874,000
• Chemical – sulphate (b)			574,000
• Chemical - sulphate (u)			300,000
• Chemical – sulphite			NA
• Dissolving			950,000
Wood charcoal	NA	295,500	**295,500**
Wood pellets			**5,000**

Notes: SW = Softwood; HW = Hardwood; NA = not available; [m³] = cubic meter; [mt] = metric ton; MDF = medium density fiberboard; HDF = high density fiberboard; (b) = bleached; (u) = unbleached

[1] Wood, which has been deliberately reduced to chips (flat, rigid and roughly squared), particles (thin and flexible), flakes, etc. from wood in the rough, processing residues or recovered wood products and has not been agglomerated. Wood chips and particles are used for producing cellulose pulp by mechanical means, by chemical means or by combining mechanical and chemical means, for the manufacture of fiberboard or particleboard, for energy or for other purposes. The specification of the chips and particles may vary in respect to dimensions and quality according to location and end-use. The pieces are in forms ranging from flat, rigid and roughly squared chips down to small, thin flexible particles. It is reported in cubic meter [m³] solid volume, excluding bark (FAO, 2022)

[2] Wood residues (including wood for agglomerates) are other wood processing co-products that has not been reduced to chips or particles and has not been agglomerated. These residues may often serve as raw material for the manufacture of certain forest products, notably pulp, particleboard and fiber board and may always be used as a source of energy. It is reported in cubic meter [m³] solid volume excluding bark. (FAO, 2022)

[3] Fuel wood, in logs, in billets, in twigs, in faggots or in similar forms. Split (Firewood) and other wood fuel simply worked (FAO, 2022)

Source: Food and Agriculture Organization (FAO) (FAO, 2018a)

Table 15 – Import and export of timber products in South Africa in 2018

Semifinished wood products	**Import**		**Export**	
Species	SW	HW	SW	HW
Volume in	[m^3]			
Sawnwood	91,580	95,900	245,000	42,440
Veneer	4,674		2,403	
Plywood	91,211		55,163	
∑ Wooden panels	**66,185**		**126,484**	
• Particle boards	28,899		109,851	
• Fiberboards (MDF/HDF)	37,286		16,633	
∑ Wood processing residues	**147,885**		**2,392,464**	
• Wood chips	147,524		2,391,352	
• Sawmill by-products	361		1,112	
Firewood	199,220	540,328	168,539	9,479
Volume in	[mt]			
∑ Wood pulp	**404,708**		**1,305,854**	
• Mech. & semi-chemical	5,185		23	
• Chemical	199,408		178,745	
• Chemical – sulphate (b)	190,037		178,686	
• Chemical - sulphate (u)	5,878		30	
• Chemical – sulphite	3,493		29	
• Dissolving	707		948,341	
Charcoal	**96,030**		**35,422**	
Wood pellets	**13,506**		**252**	

Notes: SW = Softwood; HW = Hardwood; [m^3] = cubic meter; [mt] = metric ton; MDF = medium density fiberboard; HDF = high density fiberboard; (b) = bleached; (u) = unbleached

Source: Food and Agriculture Organization (FAO) (FAO, 2018a)

Table 16 – Conversion factors for roundwood to product

Product	Unit in/ unit out	South Africa
Saw/veneer logs		
Conifer (SW)	Share %	100
Green weight with bark/green m^3 (wood only)	Kg/m^3	940
Wood basic density (dry weight of wood/green m^3 wood only)	Kg/m^3	430
Volume ratio, wood/bark plus wood	ub/ob	0.95
Pulp logs		
Conifer (SW)		
Wood basic density (dry weight of wood/green m^3, wood only)	Kg/m^3	450
Non-conifer (HW)		
Wood basic density (dry weight of wood/green m^3, wood only)	Kg/m^3	550
Wood chips		
Green swe to oven-dry tons	m^3/odmt	2.44
Average delivered tons/odmt	mt/odmt	2.19
m^3 loose to solid m^3	m^3/m^3	3.76
Sawdust		
Green swe to oven-dry tons	m^3/odmt	2.44
Average delivered tons/odmt	mt/odmt	2.19
m^3 loose to solid m^3	m^3/m^3	3.76
Shavings		
Green swe to oven-dry tons	m^3/odmt	2.44
Average delivered tons/odmt	mt/odmt	1.15
m^3 loose to solid m^3	m^3/m^3	3.76

Notes: SW = softwood, which is a synonym for conifer; HW = hardwood, which is a synonym for non-conifer; odmt = oven-dry tons; swe = solid wood equivalent (assumes green volume of wood, prior to any shrinkage); loose m^3 = indicates bulk volume (including the void space between wood particles).

Source: Forest product conversion factors (FAO et al., 2020)

Table 17 – Conversion factors and material balance of semifinished wood products (sawnwood, veneer/plywood and mining timber/wooden poles)

Product	**Unit in/ unit out**	**South Africa**
Conifer (SW)		
Sawnwood all	m^3rw/m^3p	2.08
Sawnwood green rough	m^3rw/m^3p	1.66
Sawnwood dry rough	m^3rw/m^3p	1.75
Sawnwood dry planed	m^3rw/m^3p	2.08
Material balance sawnwood SW		
Sawnwood	%	48
Chips/slabs	%	20
Sawdust	%	24
Shavings	%	5
Shrinkage	%	3
Average sawnwood shipping weight	$Kg\%m^3$	430
Plywood and veneer, green rough	m^3rw/m^3p	1.85
Material balance plywood/veneer SW		
Veneer	%	53
Other products (chips, peeler core, etc.)	%	42
Sanding dust	%	1
Shrinkage/losses	%	4
Non-conifer (HW)		**Average Africa**
Sawnwood, all	m^3rw/m^3p	1.82
Sawnwood, green rough	m^3rw/m^3p	2.15
Material balance sawnwood HW		
Sawnwood	%	55
Chips/slabs	%	21
Sawdust	%	10
Shavings	%	7
Shrinkage	%	7
Conifer and non-conifer (SW/HW)		
Utility poles (round)	m^3rw/m^3p	1.35

Notes: SW = softwood, which is a synonym for conifer; HW = hardwood; m^3rw = cubic meter roundwood; m^3p = cubic meter product.

Source: Forest product conversion factors (FAO et al., 2020)

Table 18 – Conversion factors and material balance of semifinished wood products (wood-based panels and wood pulp)

Product	**Unit in/ unit out**	**Average Latin America**
Particle board	m^3sw/m^3p	1.54
Average thickness	mm	16.5
Product basic density	Kg/m^3	667
Material balance particleboard		
Binders and fillers	%	9
Bark	%	7
Moisture	%	8
Wood	%	81
Fiberboard, hard (wet process)	m^3sw/m^3p%	2.14
Average thickness	mm	3.00
Product basic density	Kg/m^3	917
Fiberboard, medium/high (MDF/HDF)	m^3sw/m^3p%	1.53
Average thickness	mm	16.5
Product basic density	Kg/m^3	660
Material balance MDF/HDF		
Binders and fillers	%	9
Bark	%	0
Moisture	%	7
Wood	%	83
Wood pulp		
Mechanical	m^3sw/m^3p%	2.55
• Basic density of wood input	Kg/m^3	450
Sulfate bleached	m^3sw/m^3p%	4.27
• Basic density of wood input	Kg/m^3	550
Sulfate unbleached	m^3sw/m^3p%	4.27
• Basic density of wood input	Kg/m^3	450
Dissolving grades	m^3sw/m^3p%	6.54
• Basic density of wood input	Kg/m^3	600
Share of recycled fiber in total pulp	%	39

Notes: HB = hardboard; MDF= medium density fiberboard; m^3sw = cubic meter solid wood; mt = tons (in this case assumed air-dry – 10% moisture, wet basis); Kg = kilogram [1,000 gram].

Source: Forest product conversion factors (FAO et al., 2020)

Table 19 – Power generation share of solid biofuels and organic waste in South Africa in 2018

Power generation per segment	[k toe]	[GWh]	**Share** [%]
Electricity plants	136	5,689	2
CHP plants	11	441	0
Other transformations	1,863	103,579	31
Power generation	**2,009**	**109,710**	**33**
Industrial firewood	2,701	113,080	34
Household	3,197	114,514	34
Heat generation	**5,898**	**227,595**	**77**
Total power and heat generation	**7,907**	**337,305**	**100**

Notes: [K toe] = kilo metric ton of oil equivalent; [GWh] = giga watt per hour

Source: World Energy Balances by International Energy Agency (IEA) (IEA, 2018)

Table 20 – Plantation forest area in South Africa in 2018 and mean annual increment of selected species.

Plantation forest tree species	**Area** [ha]	**MAI** [1] [m^3/ha year $^{-1}$]
∑ Coniferous - Softwood	**584,338**	14.6
Pinus patula	286,017	
Pinus elliotti	169,621	
Pinus radiata	45,135	
Others	83,565	
∑ Non-coniferous - Hardwood	**607,300**	
Eucalyptus spp.	521,040	24.6
Acacia (Wattle)	81,943	9.2
Others	4,358	
∑ Planted areas	**1,191,638**	

Notes: ha = hectare, which is 10,000 square meters [m^2]; MAI = mean annual increment

Source: Area reported by the Department of Agriculture, Forestry and Fisheries (DAFF, 2018); [1] Values for MAI according to Department of Water Affairs and Forestry (DWAF, 2005).

3. Materials and methods | Invasive alien plant flows

Table 21 – Selected invasive tree species occurring in South Africa

Selected invasive tree species	**Area** [ha]
Acacia spp. • *Acacia mearnsii* De Wild. • *Acacia saligna* (Labill.) H.L.Wendl.	**28,407**
Eucalyptus spp. • *Eucalyptus camaldulensis* Dehnh. • *Eucalyptus grandis* W.Hill ex Maiden	**15,988**
Pinus spp. • *Pinus patula* Schiede ex Schltdl. & Cham. • *Pinus pinaster* Aiton • *Pinus radiate* D.Don	**30,481**
Others	**11,387**
Total	**86,263**

Notes: ha = hectare [10,000 m^2]

Source: Food and Agriculture Organization (FAO); South African National Biodiversity Institute (SANBI) (FAO, 2014b; National Environmental Management: Biodiversity Act (10/2004): Draft Alien and Invasive Species Lists, 2014)

3. Materials and methods | Agricultural crops flows

Table 22 – Area, production volumes and yield of selected agricultural field crops in South Africa in 2017 and 2018

<table>
<tr><th colspan="2">Agricultural field crops</th><th>Area
[ha]</th><th>Production
[mt]</th><th>Yield
[mt/ha]</th></tr>
<tr><td rowspan="5">Grains & cereals</td><td>Maize</td><td>2,633,685</td><td>13,103,975</td><td>4.98</td></tr>
<tr><td>Wheat</td><td>491,600</td><td>1,535,000</td><td>3.12</td></tr>
<tr><td>Sorghum</td><td>28,800</td><td>115,000</td><td>3.99</td></tr>
<tr><td>Barley</td><td>91,380</td><td>307,000</td><td>3.36</td></tr>
<tr><td>Oats | 2017</td><td>57,317</td><td>106,119</td><td>1.85</td></tr>
<tr><td rowspan="4">Oil seeds</td><td>Soya bean</td><td>787,200</td><td>1,540,000</td><td>1,96</td></tr>
<tr><td>Sunflower seed</td><td>355,660</td><td>862,000</td><td>1,43</td></tr>
<tr><td>Canola, rapeseed</td><td>68,075</td><td>93,500</td><td>1,11</td></tr>
<tr><td>Groundnut</td><td>56,300</td><td>57,000</td><td>2.05</td></tr>
<tr><td rowspan="4">Others</td><td>Sugarcane | 2017</td><td rowspan="2">186,483</td><td>7,534,550</td><td>40.40</td></tr>
<tr><td>Sugarcane bagasse | 2017</td><td>2,863,129</td><td>15.35</td></tr>
<tr><td>Horticulture | 2017</td><td>108,233</td><td></td><td></td></tr>
<tr><td>Other crops</td><td>1,116,954</td><td></td><td></td></tr>
<tr><td>∑</td><td>Total crops</td><td>5,981,687</td><td></td><td></td></tr>
</table>

Notes: ha = hectare [10,000 m²]; mt = metric ton

Source: Department of Statistics, Department of Agriculture, Forestry and Fisheries, South African Grain Information Service (SAGIS) (DAFF, 2019; Hugo, 2016; Stats SA, 2017)

Table 23 – Land use for commercial agricultural activities in South Africa in 2017

<table>
<tr><th>Farming land use</th><th>Area
[ha]</th><th>Share
[%]</th></tr>
<tr><td>40,122 farm units</td><td>46,420,458</td><td>100</td></tr>
<tr><td>∑ Arable land
• For crop production
• Cultivated pastures
• Temporarily fallow
• Others</td><td>7,614,392
5,981,687
1,306,241
297,111
29,352</td><td>16.4</td></tr>
<tr><td>∑ Grazing land
• Livestock
• Game farming</td><td>36,536,940
34,086,360
2,450,580</td><td>78.7</td></tr>
<tr><td>Other land</td><td>2,269,115</td><td>4.9</td></tr>
</table>

Notes: ha = hectare [10,000 m²]

Source: Census of Commercial Agriculture by Department of Statistics (Stats SA, 2017)

Table 24 – Conversion factor for agricultural crop field in South Africa

Agricultural field crops		Residues [%]	Soil maintenance [%]	Animal feed [%]
Grains & Cereals	Maize	74	50	35
	Wheat	57	50	35
	Sorghum	57	50	35
	Barley	55	50	35
	Oats	57	50	35
Oil Seeds	Soya bean	50	50	35
	Sunflower seed	50	50	35
	Canola, rapeseed	50	50	35
	Groundnut	81	50	35
OC	Sugarcane	22	50	0
	Sugarcane bagasse	38	50	35

Notes: OC = other crops

Source: BIOPACT; Department of Agriculture, Forestry and Fisheries (DAFF); Kim & Dale; BioEnergy Atlas (BIOPACT, 2006; DAFF, 2019; Hugo, 2016; Kim & Dale, 2004)

3. Materials and methods | Recyclable flows

Table 25 – Waste generation in South Africa in 2017

Waste type		Weight	Import	Export	Recycled	Landfilled
		[mt]			[%]	
General	Construction & demolition	4,482,992	NA	NA	52.0	48.0
	Plastics	1,113,362	6,748	20,856	43.7	56.3
	Fly-ash *(inclusive dust)*	4,346,080	NA	NA	3.1	96.9
	Bottom-ash	6,489,080	NA	NA	3.1	96.9
	Slag	4,859,025	NA	NA	NA	100
	Others	34,334,207	NA	NA	NA	NA
Total general waste		**55,624,746**	**131,196**	**690,050**	**34.5**	**65.5**
Hazardous	Fly-ash *(inclusive dust)*	33,290,115	NA	5,000	7.0	93.0
	Bottom-ash	5,874,726	50	NA	7.0	93.0
	Slag	2,923,640	1,750	NA	7.0	93.0
	Others	9,988,235	NA	NA	NA	NA
Total hazardous waste		**52,076,716**	**NA**	**NA**	**6.7**	**93.3**
Total waste		**107,701,462**	**-**	**-**	**-**	**-**

Notes: NA = not available; [mt] = metric ton

Source: State of Waste Report (SoWR) by Department of Environmental Affairs (DEA) (DEA, 2018)

References

Adegun, O. B., & Adedeji, Y. M. D. (2017). Review of economic and environmental benefits of earthen materials for housing in Africa. *Frontiers of Architectural Research*, *6*(4), 519–528. https://doi.org/10.1016/j.foar.2017.08.003

Adenuga, O. T., Mpofu, K., & Modise, K. R. (2020). An approach for enhancing optimal resource recovery from different classes of waste in South Africa: Selection of appropriate waste to energy technology. *Sustainable Futures*, *2*, 100033. https://doi.org/10.1016/j.sftr.2020.100033

Allesch, A., & Brunner, P. H. (2015). Material Flow Analysis as a Decision Support Tool for Waste Management: A Literature Review. *Journal of Industrial Ecology*, *19*(5), 753–764. https://doi.org/10.1111/jiec.12354

Arjmandi, R., Hassan, A., & Zakaria, Z. (2017). Rice husk and kenaf fiber reinforced polypropylene biocomposites. *Lignocellulosic Fibre and Biomass-Based Composite Materials*, 77–94.

Asante, B., Schmidt, G., Teixeira, R., Krause, A [Andreas], & Savastano Junior, H. (2021). Influence of wood pretreatment and fly ash particle size on the performance of geopolymer wood composite. *European Journal of Wood and Wood Products*, *79*(3), 597–609. https://doi.org/10.1007/s00107-021-01671-9

Asdrubali, F., D'Alessandro, F., & Schiavoni, S. (2015). A review of unconventional sustainable building insulation materials. *Sustainable Materials and Technologies*, *4*, 1–17. https://doi.org/10.1016/j.susmat.2015.05.002

Batidzirai, B., Valk, M., Wicke, B., Junginger, M [M.], Daioglou, V., Euler, W., & Faaij, A. (2016). Current and future technical, economic and environmental feasibility of maize and wheat residues supply for biomass energy application: Illustrated for South Africa. *Biomass and Bioenergy*, *92*, 106–129. https://doi.org/10.1016/j.biombioe.2016.06.010

Behrens, A., Giljum, S., Kovanda, J., & Niza, S. (2007). The material basis of the global economy. *Ecological Economics*, *64*(2), 444–453. https://doi.org/10.1016/j.ecolecon.2007.02.034

Ben-Alon, L., Loftness, V., Harries, K. A., DiPietro, G., & Hameen, E. C. (2019). Cradle to site Life Cycle Assessment (LCA) of natural vs conventional building materials: A case study on cob earthen material. *Building and Environment*, *160*, 106150. https://doi.org/10.1016/j.buildenv.2019.05.028

Bhatt, A., Priyadarshini, S., Acharath Mohanakrishnan, A., Abri, A., Sattler, M., & Techapaphawit, S. (2019). Physical, chemical, and geotechnical properties of coal fly ash: A global review. *Case Studies in Construction Materials*, *11*, e00263. https://doi.org/10.1016/j.cscm.2019.e00263

BIOPACT. (2006). *The spirit of Rudolf Diesel: peanuts and socialism*. http://global.mongabay.com/news/bioenergy/2006/09/spirit-of-rudolf-diesel-peanuts-and.html

Bowd, R., Quinn, N. W., Kotze, D. C., & Guilfoyle, M. J. (2018). A systems approach to risk and resilience analysis in the woody-biomass sector: A case study of the failure of the South African wood pellet industry. *Biomass and Bioenergy*, *108*, 126–137. https://doi.org/10.1016/j.biombioe.2017.10.032

Briggs, D. G. (1994). *Forest products measurements and conversion factors: with special emphasis on the U.S.* University of Washington. http://www.ruraltech.org/projects/conversions/briggs_conversions/briggs_book.asp

Brosowski, A., Thrän, D., Mantau, U., Mahro, B., Erdmann, G., Adler, P., Stinner, W., Reinhold, G., Hering, T., & Blanke, C. (2016). A review of biomass potential and current utilisation – Status quo for 93 biogenic wastes and residues in Germany. *Biomass and Bioenergy*, *95*, 257–272. https://doi.org/10.1016/j.biombioe.2016.10.017

Brunner, P. H., & Rechberger, H. (2016). *Handbook of Material Flow Analysis*. CRC Press. https://doi.org/10.1201/9781315313450

Buddi, T., Muttil, N., Rao, B. N., & Singh, S. K. (2015). Development of a Soya Based Adhesive in Plywood Manufacturing. *Materials Today: Proceedings*, *2*(4-5), 3027–3031. https://doi.org/10.1016/j.matpr.2015.07.289

Buddi, T., Singh, S. K., & Nageswara Rao, B. (2018). Optimum Process Parameters for Plywood Manufacturing using Soya Meal Adhesive. *Materials Today: Proceedings*, *5*(9), 18739–18744. https://doi.org/10.1016/j.matpr.2018.06.220

Canavan, S., Richardson, D. M [David M.], Le Roux, J. J., Kelchner, S. A., & Wilson, J. R [John R.U.] (2021). The status of alien bamboos in South Africa. *South African Journal of Botany*, *138*, 33–40. https://doi.org/10.1016/j.sajb.2020.11.027

Canavan, S., Richardson, D. M [David M.], Le Roux, J. J., & Wilson, J. R. U. (2019). Alien Bamboos in South Africa: a Socio-Historical Perspective. *Human Ecology*, *47*(1), 121–133. https://doi.org/10.1007/s10745-018-0041-8

Castaldelli, V. N., Akasaki, J. L., Melges, J. L. P., Tashima, M. M., Soriano, L., Borrachero, M. V [María V.], Monzó, J [José], & Payá, J [Jordi] (2013). Use of Slag/Sugar Cane Bagasse Ash (SCBA) Blends in the Production of Alkali-Activated Materials. *Materials (Basel, Switzerland)*, *6*(8), 3108–3127. https://doi.org/10.3390/ma6083108

CEN European Committee for Standardization (2014). *Composites made from cellulose-based materials and thermoplastics (usually called wood-polymer composites (WPC) or natural fibre composites (NFC):* Part 1: Test methods for characterisation of compounds and products (CEN EN 15534-1). Brussels.

Clark, D., Fonseca, M., McCusker, A., Pepke, E., Prins, C., & Steierer, F. (2010). *Forest product conversion factor for the UNECE region*. Geneva.

DAFF. (2018). *Commercial timber resources and primary roundwood processing in South Africa 2017/2018*. Pretoria. Department of Agriculture, Forestry and Fisheries.

DAFF. (2019). *Abstract of Agricultural Statistics 2019*. Pretoria, South Africa. Department of Agriculture, Forestry and Fisheries. https://www.daff.gov.za/daffweb3/Home/Crop-Estimates/Statistical-Information

DAFF. (2020). *Protected Areas Register (PAR): 4. Proportion of area under conservation.* Department of Agriculture, Forestry and Fisheries. https://portal.environment.gov.za/portal/apps/webappviewer/index.html?id=54487a82babf4a7e9ab3a42aacabdf84

DEA. (2012). *National Waste Information Baseline Report*. Draft (28p). Pretoria, South Africa. Department of Environmental Affairs.

National Environmental Management: Biodiversity Act (10/2004): Draft Alien and Invasive Species Lists, Department of Environmental Affairs (2014). https://www.sanbi.org/wp-content/uploads/2018/04/nembainvasivealienspeciesregulations-12feb2014.pdf

DEA. (2018). *South Africa State of Waste: A report on the state of the environment*. Final draft report (ISBN 978-0-621-46843-4). Pretoria. Department of Environmental Affairs.

Desing, H., Braun, G., & Hischier, R. (2021). Resource pressure – A circular design method. *Resources, Conservation and Recycling*, *164*, 105179. https://doi.org/10.1016/j.resconrec.2020.105179

Díaz-Ramírez, G., Maradei, F., & Vargas-Linares, G. (2019). Bagasse sugarcane fibers as reinforcement agents for natural composites: description and polymer composite applications. *Revista UIS Ingenierías*, *18*(4), 117–130. https://doi.org/10.18273/revuin.v18n4-2019011

Dovey, S. B. (2009). Estimating biomass and macronutrient content of some commercially important plantation species in South Africa. *Southern Forests: A Journal of Forest Science*, *71*(3), 245–251. https://doi.org/10.2989/SF.2009.71.3.9.921

Duxson, P., Provis, J. L., Lukey, G. C., & van Deventer, J. S. (2007). The role of inorganic polymer technology in the development of 'green concrete'. *Cement and Concrete Research*, *37*(12), 1590–1597. https://doi.org/10.1016/j.cemconres.2007.08.018

DWAF. (2004). *Roundwood supply and demand to 2030: A sub-sector analysis*. Pretoria. Department of Water Affairs and Forestry.

DWAF. (2005). *Study of Supply and Demand of Industrial Roundwood in South Africa: Period 2005 to 2034.* Department of Water Affairs and Forestry.

Eckelman, M. J., & Chertow, M. R. (2009). Using Material Flow Analysis to Illuminate Long-Term Waste Management Solutions in Oahu, Hawaii. *Journal of Industrial Ecology*, *13*(5), 758–774. https://doi.org/10.1111/j.1530-9290.2009.00159.x

Eloka-Eboka, A. C., Igbum, G. O., & Inambao, F. L. (2017). Biodiesel methyl ester production and testing from selected African tropical seed oil feedstocks. *Energy Procedia*, *142*, 755–767. https://doi.org/10.1016/j.egypro.2017.12.123

Emdadi, Z., Asim, N., Ambar Yarmo, M., Shamsudin, R., Mohammad, M., & Sopian, K [Kamaruzaman] (2016). Green Material Prospects for Passive Evaporative Cooling Systems: Geopolymers. *Energies*, *9*(8), 586. https://doi.org/10.3390/en9080586

Emdadi, Z., Asim, N., Amin, M., Ambar Yarmo, M., Maleki, A., Azizi, M., & Sopian, K [Kamaruzzaman] (2017). Development of Green Geopolymer Using Agricultural and Industrial Waste Materials with High Water Absorbency. *Applied Sciences*, *7*(5), 514. https://doi.org/10.3390/app7050514

Essel, R., & Reichenbach, J. (2016). *CASCADES: Study on the optimised cascading use of wood* (M. Vis, U. Mantau, & B. Allen, Eds.). Publications Office.

European Commission. (2020). *A new Circular Economy Action Plan: For a cleaner and more competitive Europe*. Brussels. https://eur-lex.europa.eu/legal-content/EN/TXT/HTML/?uri=CELEX:52020DC0098&from=EN

Directive 2008/98/EC of the European Parliament and of the council of 19 November 2008 on waste and repealing certain, 2008. https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A32008L0098

FAO. (2014a). *BioEnergy and Food Security rapid appraisal (BEFS RA) Natural Resources Module: Agricultural Residues Component: crop residues and livestock residues*. User manual.

FAO. (2014b). *Global forest resources assessment: Country report South Africa*. Rome, Italy.

FAO. (2018a). *FAOSTAT: Forestry Production and Trade*. http://www.fao.org/faostat/en/#data/FO

FAO. (2018b). *Forest Resources Assessment: Terms and definitions*. Forest resource assessment working paper. Rome, Italy.

FAO. (2020). *Global Forest Resources Assessment 2020: Report South Africa*. Rome. Food and Agriculture Organisation of United Nations.

FAO. (2022). *Classification of forest products* (Forestry Working Paper 29). Rome. Food and Agriculture Organization of United Nations. https://www.fao.org/forestry/statistics/80572/en/ https://doi.org/10.4060/cb8216en

FAO, ITTO, & United Nations. (2020). *Forest product conversion factors*. FAO, ITTO and United Nations. https://doi.org/10.4060/ca7952en

Ferreira, C., Ribeiro, A., & Ottosen, L. (2003). Possible applications for municipal solid waste fly ash. *Journal of Hazardous Materials*, *96*(2-3), 201–216. https://doi.org/10.1016/S0304-3894(02)00201-7

FLYABILITY SA. *What is backfilling in mining? Types of Backfill; The Mine Backfilling Process; Mine Backfilling Process Hazards; Advantages and Disadvantages of Backfill Mining*. https://www.flyability.com/backfilling

Fonseca, M. (2010). *Forest product conversion factors for the UNECE region*. Geneva.

Gibson, L., Münch, Z., Palmer, A., & Mantel, S. (2018). Future land cover change scenarios in South African grasslands - implications of altered biophysical drivers on land management. *Heliyon*, *4*(7), e00693. https://doi.org/10.1016/j.heliyon.2018.e00693

Godsmark, R., & Oberholzer, F. (2019). *South African Forestry and Forest Products Industry: January 2019.* Forestry South Africa.

Göswein, V., Silvestre, J. D [José Dinis], Lamb, S., Gonçalves, A. B., Pittau, F., Freire, F., Oosthuizen, D., Lord, A., & Habert, G. (2021). Invasive alien plants as an alternative resource for concrete production – multi-scale optimization including carbon compensation, cleared land and saved water runoff in South Africa. *Resources, Conservation and Recycling*, *167*, 105361. https://doi.org/10.1016/j.resconrec.2020.105361

Guild, J., & Shackleton, C. M. (2018). Informal urban fuelwood markets in South Africa in the context of socio-economic change. *Energy Policy*, *117*, 136–141. https://doi.org/10.1016/j.enpol.2018.03.023

Gupta, A. (2017). Building a Green Home Using Local Resources and Sustainable Technology in Jammu Region – A Case Study. *Energy Procedia*, *115*, 59–69. https://doi.org/10.1016/j.egypro.2017.05.007

He, J., Kawasaki, S., & Achal, V. (2020). The Utilization of Agricultural Waste as Agro-Cement in Concrete: A Review. *Sustainability*, *12*(17), 6971. https://doi.org/10.3390/su12176971

Henderson, L [L.] (2007). Invasive, naturalized and casual alien plants in southern Africa: a sum-mary based on the Southern African Plant Invaders Atlas (SAPIA). *Bothalia*, *37*(2), 215–248. https://doi.org/10.4102/abc.v37i2.322

Henderson, L [Lesley], & Wilson, J. R [John R.U.] (2017). Changes in the composition and distribution of alien plants in South Africa: An update from the Southern African Plant Invaders Atlas. *Bothalia*, *47*(2). https://doi.org/10.4102/abc.v47i2.2172

Hildebrandt, J., Hagemann, N., & Thrän, D. (2017). The contribution of wood-based construction materials for leveraging a low carbon building sector in Europe. *Sustainable Cities and Society*, *34*, 405–418. https://doi.org/10.1016/j.scs.2017.06.013

Hugo, W. (2015). *Availability of Exploitable Invasive Alien Plants: South African BioEnergy Atlas*. Section WP06_03. Pretoria, South Africa. South African Environmental Observation Network. http://bea.dirisa.org/atlas/biomass

Hugo, W. (2016). *BioEnergy Atlas for South Africa: Synopsis Report*. Pretoria, South Africa. Department of Science and Technology. https://doi.org/10.15493/SAEON.BEA.DOCS.10000001

Hung, K.-C., Yeh, H., Yang, T.-C., Wu, T.-L., Xu, J.-W., & Wu, J.-H. (2017). Characterization of Wood-Plastic Composites Made with Different Lignocellulosic Materials that Vary in Their Morphology, Chemical Composition and Thermal Stability. *Polymers*, *9*(12). https://doi.org/10.3390/polym9120726

IEA. (2018). *World Energy Balances Overview: Renewable and waste*. https://www.iea.org/data-and-statistics/data-tables/?country=SOUTHAFRIC&energy=Renewables%20%26%20waste&year=2018

ILO. (2015). *Guidelines for a just transition towards environmentally sustainable economies and societies for all*. Geneva, Switzerland. International Labour Organization.

Jacob, P., Kashyap, P., Suparat, T., & Visvanathan, C. (2014). Dealing with emerging waste streams: Used tyre assessment in Thailand using material flow analysis. *Waste Management & Research : The Journal of the International Solid Wastes and Public Cleansing Association, ISWA*, *32*(9), 918–926. https://doi.org/10.1177/0734242X14543554

Jawaid, M., Tahir, P. M., & Saba, N. (2017). Introduction to biomass and its composites. *Lignocellulosic Fibre and Biomass-Based Composite Materials*, 1–11.

Jin, S. L., Schure, J., Ingram, V., & Yoo, B. I. (2017). *Sustainable woodfuel for food security: A smart choice: green, renewable and affordable* (D. Reeb, Z. Xia, A. Perlis, M. Nordberg, J. Campbell, & E. Muller, Eds.). Food and Agriculture Organization of the United Nations.

Kamdem, D., Jiang, H., Cui, W., Freed, J., & Matuana, L. M. (2004). Properties of wood plastic composites made of recycled HDPE and wood flour from CCA-treated wood removed from service. *Composites Part a: Applied Science and Manufacturing*, *35*(3), 347–355. https://doi.org/10.1016/j.compositesa.2003.09.013

Kazemi Najafi, S. (2013). Use of recycled plastics in wood plastic composites - a review. *Waste Management (New York, N.Y.)*, *33*(9), 1898–1905. https://doi.org/10.1016/j.wasman.2013.05.017

Khoodaruth, A. (2014). Optimisation of a Cogenerated Energy Systems: The Cane Biomass Flexi-factory Case Study. *Energy Procedia*, *62*, 656–665. https://doi.org/10.1016/j.egypro.2014.12.429

Kim, S., & Dale, B. E. (2004). Global potential bioethanol production from wasted crops and crop residues. *Biomass and Bioenergy*, *26*(4), 361–375. https://doi.org/10.1016/j.biombioe.2003.08.002

Kiyanets, A. V. (2016). Resource-saving Construction Technologies. *Procedia Engineering*, *150*, 2124–2127. https://doi.org/10.1016/j.proeng.2016.07.251

Kooduvalli, K., Sharma, B., Webb, E., Vaidya, U., & Ozcan, S. (2019). Sustainability Indicators for Biobased Product Manufacturing: A Systematic Review. *Journal of Sustainable Development*, *12*(1), 55. https://doi.org/10.5539/jsd.v12n1p55

Kraaij, T., Baard, J. A., Rikhotso, D. R., Cole, N. S., & van Wilgen, B. W. (2017). Assessing the effectiveness of invasive alien plant management in a large fynbos protected area. *Bothalia*, *47*(2). https://doi.org/10.4102/abc.v47i2.2105

Krause, K., Sauerbier, P., Koddenberg, T., & Krause, A [Andreas] (2018). Utilization of Recycled Material Sources for Wood-Polypropylene Composites: Effect on Internal Composite Structure, Particle Characteristics and Physico-Mechanical Properties. *Fibers*, *6*(4), 86. https://doi.org/10.3390/fib6040086

Kriel, G. (2020). *Poultry Farming in South Africa: Poultry Bedding*. http://southafrica.co.za/poultry-bedding.html

Kroehong, W., Jaturapitakkul, C., Pothisiri, T., & Chindaprasirt, P. (2018). Effect of Oil Palm Fiber Content on the Physical and Mechanical Properties and Microstructure of High-Calcium Fly Ash Geopolymer Paste. *Arabian Journal for Science and Engineering*, *43*(10), 5215–5224. https://doi.org/10.1007/s13369-017-3059-0

Kurda, R., Silvestre, J. D [José D.], & Brito, J. de (2018). Toxicity and environmental and economic performance of fly ash and recycled concrete aggregates use in concrete: A review. *Heliyon*, *4*(4), e00611. https://doi.org/10.1016/j.heliyon.2018.e00611

Laner, D., Feketitsch, J., Rechberger, H., & Fellner, J. (2016). A Novel Approach to Characterize Data Uncertainty in Material Flow Analysis and its Application to Plastics Flows in Austria. *Journal of Industrial Ecology*, *20*(5), 1050–1063. https://doi.org/10.1111/jiec.12326

Liu, L., Li, H., Lazzaretto, A., Manente, G., Tong, C., Liu, Q., & Li, N. (2017). The development history and prospects of biomass-based insulation materials for buildings. *Renewable and Sustainable Energy Reviews*, *69*, 912–932. https://doi.org/10.1016/j.rser.2016.11.140

Luhar, S., Cheng, T.-W., & Luhar, I. (2019). Incorporation of natural waste from agricultural and aquacultural farming as supplementary materials with green concrete: A review. *Composites Part B: Engineering*, *175*, 107076. https://doi.org/10.1016/j.compositesb.2019.107076

Maema, L. P., Potgieter, M. J., & Samie, A. (2019). Ethnobotanical survey of invasive alien plant species used in the treatment of sexually transmitted infections in Waterberg District, South Africa. *South African Journal of Botany*, *122*, 391–400. https://doi.org/10.1016/j.sajb.2019.01.012

Malitz, G. von. (2003). *Classification system for South African indigenous forests: An objective classification for the Department of Water Affairs and Forestry.* Department of Agriculture, Forestry and Fisheries Forestry.

Malkawi, A. B., Habib, M., Aladwan, J., & Alzubi, Y. (2020). Engineering properties of fibre reinforced lightweight geopolymer concrete using palm oil biowastes. *Australian Journal of Civil Engineering*, *18*(1), 82–92. https://doi.org/10.1080/14488353.2020.1721954

Mantau, U. (2015). Wood flow analysis: Quantification of resource potentials, cascades and carbon effects. *Biomass and Bioenergy*, *79*, 28–38. https://doi.org/10.1016/j.biombioe.2014.08.013

Maraveas, C. (2020). Production of Sustainable Construction Materials Using Agro-Wastes. *Materials (Basel, Switzerland)*, *13*(2). https://doi.org/10.3390/ma13020262

Mbedzi, M., Tshisikhawe, M. P., Sinthumule, N. I., & Rahlao, S. (2018). The rate of regeneration of native plant species after the eradication of invasive alien plant species in Limpopo Province, South Africa. *South African Journal of Botany*, *115*, 298. https://doi.org/10.1016/j.sajb.2018.02.081

Memon, S. A., Khan, S., Wahid, I., Shestakova, Y., & Ashraf, M. (2020). Evaluating the Effect of Calcination and Grinding of Corn Stalk Ash on Pozzolanic Potential for Sustainable Cement-Based Materials. *Advances in Materials Science and Engineering*, *2020*, 1–13. https://doi.org/10.1155/2020/1619480

Mensah, S., Pienaar, O. L., Kunneke, A., Du Toit, B., Seydack, A., Uhl, E., Pretzsch, H., & Seifert, T. (2018). Height – Diameter allometry in South Africa's indigenous high forests: Assessing generic models performance and function forms. *Forest Ecology and Management*, *410*, 1–11. https://doi.org/10.1016/j.foreco.2017.12.030

Mohlala, L. M., Bodunrin, M. O., Awosusi, A. A., Daramola, M. O., Cele, N. P., & Olubambi, P. A. (2016). Beneficiation of corncob and sugarcane bagasse for energy generation and materials development in Nigeria and South Africa: A short overview. *Alexandria Engineering Journal*, *55*(3), 3025–3036. https://doi.org/10.1016/j.aej.2016.05.014

Motaung, T. E., & Linganiso, L. Z. (2018). Critical review on agrowaste cellulose applications for biopolymers. *International Journal of Plastics Technology*, *22*(2), 185–216. https://doi.org/10.1007/s12588-018-9219-6

Muazu, N. B., Ogujiuba, K., & Tukur, H. R. (2020). Biomass Energy Dependence in South Africa: Are the Western Cape Province households descending the energy ladder after improvement in electricity access? *Energy Reports*, *6*, 207–213. https://doi.org/10.1016/j.egyr.2020.11.267

Mucina, L [Ladislav] (Ed.). (2014). *Strelitzia: Vol. 33*. *Vegetation field atlas of continental South Africa, Lesotho and Swaziland*. SANBI.

Mwanza, B. G., & Mbohwa, C. (2017). Drivers to Sustainable Plastic Solid Waste Recycling: A Review. *Procedia Manufacturing*, *8*, 649–656. https://doi.org/10.1016/j.promfg.2017.02.083

Nasrullah, A., Bhat, A. H., Sada Khan, A., & Ajab, H. (2017). Comprehensive approach on the structure production, processing and application of lignin. *Lignocellulosic Fibre and Biomass-Based Composite Materials*, 166–178.

Nkambule, N. P., Blignaut, J. N., Vundla, T., Morokong, T., & Mudavanhu, S. (2017). The benefits and costs of clearing invasive alien plants in northern Zululand, South Africa. *Ecosystem Services*, *27*, 203–223. https://doi.org/10.1016/j.ecoser.2017.04.011

Nourbakhsh, A., & Ashori, A. (2010). Wood plastic composites from agro-waste materials: Analysis of mechanical properties. *Bioresource Technology*, *101*(7), 2525–2528. https://doi.org/10.1016/j.biortech.2009.11.040

Ogundipe, K. E., Ogunbayo, B. F., Olofinnade, O. M., Amusan, L. M., & Aigbavboa, C. O. (2021). Affordable housing issue: Experimental investigation on properties of eco-friendly lightweight concrete produced from incorporating periwinkle and palm kernel shells. *Results in Engineering*, *9*, 100193. https://doi.org/10.1016/j.rineng.2020.100193

Olayiwola, H. O., Amiandamhen, S. O., Meincken, M., & Tyhoda, L. (2021). Investigating the suitability of fly ash/metakaolin-based geopolymers reinforced with South African alien invasive wood and sugarcane bagasse residues for use in outdoor conditions. *European Journal of Wood and Wood Products.* Advance online publication. https://doi.org/10.1007/s00107-020-01636-4

Omokhua, A. G., Ondua, M., van Staden, J., & McGaw, L. J. (2019). Synergistic activity of extracts of three South African alien invasive weeds combined with conventional antibiotics against selected opportunistic pathogens. *South African Journal of Botany*, *124*, 251–257. https://doi.org/10.1016/j.sajb.2019.05.023

Omokhua, A. G., van Staden, J., & McGaw, L. J. (2018). The role of southern Africa alien invasive plants in the search for new antibiotics. *South African Journal of Botany*, *115*, 304. https://doi.org/10.1016/j.sajb.2018.02.104

Opoku, R., Obeng, G. Y., Darkwa, J., & Kwofie, S. (2020). Minimizing heat transmission loads and improving energy efficiency of building envelopes in sub-Saharan Africa using bio-based composite materials. *Scientific African*, *8*, e00358. https://doi.org/10.1016/j.sciaf.2020.e00358

OVAM. (2015). *Action Plan for the Sustainable Management of (Residual) Biomass Streams 2015-2020*. https://www.ovam.be/sites/default/files/atoms/files/Action%20Plan%20for%20the%20Sustainable%20Management%20of%20Biomass%20Streams%202015-2020.pdf

PAMSA. (2010). *Paper Manufacturers Association of South Africa 2010 REPORT: Overall summary: January– December 2010* [Table 6: Raw Material Consumption].

PAMSA. (2018). *Production statistics: Production summary 2018.* Paper Manufacturers Association of South Africa. https://www.thepaperstory.co.za/the-economic-story/production-statistics/

Payá, J [J.], Monzó, J [J.], Borrachero, M. V [M. V.], Díaz-Pinzón, L., & Ordóñez, L. M. (2002). Sugar-cane bagasse ash (SCBA): studies on its properties for reusing in concrete production. *Journal of Chemical Technology & Biotechnology*, *77*(3), 321–325. https://doi.org/10.1002/jctb.549

Pelkmans, L., & Bali, T. (2018). *Country reports - South Africa 2018 update: Bioenergy policies and status of implementation.* IEA Bioenergy. https://doi.org/10.1787/ned-2010-4-en-fr

Plastics SA. (2018). *National Plastics Recycling Survey.*

Plastics SA. (2019). *South African Plastics: Recycling Survey*. Executive Summary.

Potadar, O. V., & Kadam, G. S. (2018). Preparation and Testing of Composites using Waste Groundnut Shells and Coir Fibres. *Procedia Manufacturing*, *20*, 91–96. https://doi.org/10.1016/j.promfg.2018.02.013

Ribeiro, B., Uchiyama, T., Tomiyama, J., Yamamoto, T., & Yamashiki, Y. (2020). Development of Interlocking Concrete Blocks with Added Sugarcane Residues. *Fibers*, *8*(10), 61. https://doi.org/10.3390/fib8100061

Richardson, D. M [David M.], Foxcroft, L. C., Latombe, G., Le Maitre, D. C., Rouget, M [Mathieu], & Wilson, J. R [John R.]. (2020). The Biogeography of South African Terrestrial Plant Invasions. In B. W. van Wilgen, J. Measey, D. M. Richardson, J. R. Wilson, & T. A. Zengeya (Eds.), *Invading Nature - Springer Series in Invasion Ecology: Vol. 14. Biological Invasions in South Africa* (1st ed., pp. 67–96). Springer International Publishing; Imprint: Springer. https://doi.org/10.1007/978-3-030-32394-3_3

Rodier, L., Villar-Cociña, E., Ballesteros, J. M., & Junior, H. S. (2019). Potential use of sugarcane bagasse and bamboo leaf ashes for elaboration of green cementitious materials. *Journal of Cleaner Production*, *231*, 54–63. https://doi.org/10.1016/j.jclepro.2019.05.208

Rojas, C., Cea, M., Iriarte, A., Valdés, G., Navia, R., & Cárdenas-R, J. P. (2019). Thermal insulation materials based on agricultural residual wheat straw and corn husk biomass, for application in sustainable buildings. *Sustainable Materials and Technologies*, *20*, e00102. https://doi.org/10.1016/j.susmat.2019.e00102

Rouget, M [M.], Hui, C., Renteria, J., Richardson, D. M [D. M.], & Wilson, J [J.R.U.] (2015). Plant invasions as a biogeographical assay: Vegetation biomes constrain the distribution of invasive alien species assemblages. *South African Journal of Botany*, *101*, 24–31. https://doi.org/10.1016/j.sajb.2015.04.009

RSA. (2012). *National Development Plan 2030: Our future - Make it work*. National Planning Commission.

Rutherford, M. C., Mucina, L [L.], & Powrie, L. W. (2006). Biomes and bioregions of Southern Africa. *Strelitzia*(19).

Sá Ribeiro, R. A., Sá Ribeiro, M. G., Sankar, K., & Kriven, W. M. (2016). Geopolymer-bamboo composite – A novel sustainable construction material. *Construction and Building Materials*, *123*, 501–507. https://doi.org/10.1016/j.conbuildmat.2016.07.037

Saal, U., Iost, S., & Weimar, H. (2022). Supply of wood processing residues – a basic calculation approach and its application on the example of wood packaging. *Trees, Forests and People*, *7*, 100199. https://doi.org/10.1016/j.tfp.2022.100199

Saal, U., Weimar, H., & Mantau, U. (2019). Wood Processing Residues. *Advances in Biochemical Engineering/biotechnology*, *166*, 27–41. https://doi.org/10.1007/10_2016_69

SANBI. (2020). *Threatened Species Programme*. http://redlist.sanbi.org/

Sarmin, S. N., Welling, J [J.], Krause, A [A.], & Shalbafan, A. (2014). Investigating the possibility of geopolymer to produce inorganic-bonded wood composites for multifunctional construction material - A Review, *9(4)*, 7941–7950.

Schwab, O., Zoboli, O., & Rechberger, H. (2017). A Data Characterization Framework for Material Flow Analysis. *Journal of Industrial Ecology*, *21*(1), 16–25. https://doi.org/10.1111/jiec.12399

Schwarzkopf, M. J., & Burnard, M. D. (2016). Wood-Plastic Composites—Performance and Environmental Impacts. In A. Kutnar & S. S. Muthu (Eds.), *Environmental Footprints and Eco-design of Products and Processes. Environmental Impacts of Traditional and Innovative Forest-based Bioproducts* (pp. 19–43). Springer Singapore. https://doi.org/10.1007/978-981-10-0655-5_2

Schweinle, J., Geng, N., Iost, S., Weimar, H., & Jochem, D. (2020). Monitoring Sustainability Effects of the Bioeconomy: A Material Flow Based Approach Using the Example of Softwood Lumber and Its Core Product Epal 1 Pallet. *Sustainability*, *12*(6), 2444. https://doi.org/10.3390/su12062444

Shanmugam, V., Mensah, R. A., Försth, M., Sas, G., Restás, Á., Addy, C., Xu, Q., Jiang, L., Neisiany, R. E., Singha, S., George, G., Jose E, T., Berto, F., Hedenqvist, M. S., Das, O., & Ramakrishna, S. (2021). Circular economy in biocomposite development: State-of-the-art, challenges and emerging trends. *Composites Part C: Open Access*, *5*, 100138. https://doi.org/10.1016/j.jcomc.2021.100138

Sheshmani, S. (2013). Effects of extractives on some properties of bagasse/high density polypropylene composite. *Carbohydrate Polymers*, *94*(1), 416–419. https://doi.org/10.1016/j.carbpol.2013.01.067

Sommerhuber, P. F. (2016). *Resource efficiency of wood-plastic composites: Identifying secondary material substitution potentials and an environmentally sound end-of-life treatment* [Doctoral degree]. Universität Hamburg, Hamburg.

Sommerhuber, P. F., Welling, J [Johannes], & Krause, A [Andreas] (2015). Substitution potentials of recycled HDPE and wood particles from post-consumer packaging waste in Wood-Plastic Composites. *Waste Management (New York, N.Y.)*, *46*, 76–85. https://doi.org/10.1016/j.wasman.2015.09.011

Soneye, T., Ede, A. N., Bamigboye, G. O., & Olukanni, D. O. (Eds.) (2016). *The Study of Periwinkle Shells as Fine and Coarse Aggregate in Concrete Works*.

Stats SA. (2012). *Census 2011 - Census in brief* (Report no.: 03-01-41). Pretoria, South Africa. Statistics South Africa.

Stats SA. (2016). *Community Survey 2016 in Brief: Report 03-01-06*. Pretoria.

Stats SA. (2017). *Census of commercial agriculture: Financial and production statistics.* Department of Statistics. http://www.statssa.gov.za/publications/Report-11-02-01/Report-11-02-012017.pdf

Stats SA. (2020). *General Household Survey* (Statistical Release P0318). Pretoria. Department of Statistics.

Stegmann, P., Londo, M., & Junginger, M [Martin] (2020). The circular bioeconomy: Its elements and role in European bioeconomy clusters. *Resources, Conservation & Recycling: X*, *6*, 100029. https://doi.org/10.1016/j.rcrx.2019.100029

Suárez, L., Castellano, J., Díaz, S., Tcharkhtchi, A., & Ortega, Z. (2021). Are Natural-Based Composites Sustainable? *Polymers*, *13*(14). https://doi.org/10.3390/polym13142326

Sullens, W., Hooper, B., Lent, T., Geiger, C., & Vallette, J. (2015). *Optimizing Recycling: Criteria for Comparing and Improving Recycled Feedstocks in Building Products.* StopWaste; San Francisco Department of the Environment. https://healthybuilding.net/reports/9-optimizing-recycling-criteria-for-comparing-and-improving-recycled-feedstocks-in-building-products

Troschinetz, A. M., & Mihelcic, J. R. (2009). Sustainable recycling of municipal solid waste in developing countries. *Waste Management (New York, N.Y.)*, *29*(2), 915–923. https://doi.org/10.1016/j.wasman.2008.04.016

UNEP, ILO, IOE, & ITUC. (2008). *Green Jobs: Towards decent work in a sustainable, low-carbon world*. Nairoby, Kenya. United Nations Environment Programme; International Labour Organization; International Organization of Employers; International Trade Union Confederation.

United Nations. (2019). *World Population Prospects: The 2019 Revision*. New York.

van Deventer, J. S., Provis, J. L., & Duxson, P. (2012). Technical and commercial progress in the adoption of geopolymer cement. *Minerals Engineering*, *29*, 89–104. https://doi.org/10.1016/j.mineng.2011.09.009

van Wilgen, B. W., Measey, J., Richardson, D. M [David M.], Wilson, J. R [John R.], & Zengeya, T. A. (Eds.). (2020). *Invading Nature - Springer Series in Invasion Ecology: Vol. 14*. *Biological Invasions in South Africa* (1st ed. 2020). Springer International Publishing; Imprint: Springer. https://doi.org/10.1007/978-3-030-32394-3

van Wilgen, B. W., & Wilson, J. R [J. R.]. (2018). *The status of biological invasions and their management in South Africa in 2017*. Pretoria, South Africa. South African National Biodiversity Institute.

Vujic, G., Jovicic, N., Babic, M., Stanisavljevic, N., Batinic, B., & Pavlovic, A. (2010). Assessment of plastic flows and stocks in Serbia using material flow analysis. *Thermal Science*, *14*(suppl), 89–95. https://doi.org/10.2298/TSCI100621031V

Ye, H., Zhang, Y., & Yu, Z. (2018). Wood Flour's Effect on the Properties of Geopolymer-based Composites at Different Curing Times. *BioResources*, *13*(2). https://doi.org/10.15376/biores.13.2.2499-2514

Youssef, A. M., Hasanin, M. S., Abd El-Aziz, M. E., & Darwesh, O. M. (2019). Green, economic, and partially biodegradable wood plastic composites via enzymatic surface modification of lignocellulosic fibers. *Heliyon*, *5*(3), e01332. https://doi.org/10.1016/j.heliyon.2019.e01332

Zerbo, A., Castro Delgado, R., & González, P. A. (2020). A review of the risk of cholera outbreaks and urbanization in sub-Saharan Africa. *Journal of Biosafety and Biosecurity*, *2*(2), 71–76. https://doi.org/10.1016/j.jobb.2020.11.004

Statutory declaration

I herewith declare that I have completed the present thesis independently making use only of the specified literature and auxiliary sources. Identification of references about the statement and scope of the work is quoted. The thesis in this form or in any other form has not been submitted to an examination body and has not been published so far. The print version is a complete replication of the digital one.

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Hamburg, 2022-11-21

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