Microbial Carbonisation and its potential for on-farm composting

– exploring reductive composting as an approach for regenerative agriculture

Mikrobielle Carbonisierung und ihr Potential für landwirtschaftliche Kompostierung – Untersuchung reduktiver Kompostierung als Ansatz für die regenerative Landwirtschaft

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Abstract

The search for agronomic solutions to the decline of soil health, open-ended nutrient cycles and greenhouse gas (GHG) emissions from agriculture, against the background of impending climate change, were motivations for this thesis. A composting trial on a Swedish farm was designed to find answers to the overarching research question of how feasible and climate-friendly on-farm composting using Microbial Carbonisation (MC) is, compared to conventional windrow composting (CC). MC can be understood as the biological transformation of biomass under mesophilic and anoxic conditions, in contrast to CC, which is an aerobic and partly thermophilic decomposition process.

The investigation of the MC method was approached using natural and social science methodologies. Field trials were carried out, accompanied by substrate, soil, emission and pore-gas measurements, as well as records of machinery use. In addition, interviews were conducted with farmers already using MC in Germany, to gain a better insight into its practical application and farmers' needs.

The results suggest that MC substrates can be richer in nitrogen (N) and carbon (C) after composting than CC. The machinery requirement of MC was only one tenth of the more labour-intensive CC process, which is associated with lower fossil emissions. A novelty of the present research was that nitrous oxide (N_2O) emissions were measured for the first time on a MC compost. Overall, on a weight basis, MC showed 30 – 40 % lower GHG emissions during composting, compared to CC. This advantage, however, was offset by 28 – 40 % higher emissions in the field on an area basis. In addition, GHG balances are highly dependent on the appropriateness of the measurement-methodology, the period under consideration and the reference unit in which the emissions are expressed. As CC showed higher N-losses during the composting process, MC overall emitted 5 – 29 % less GHG per kg N applied to the field. It was therefore not entirely clear whether MC or CC performed better in terms of GHG emissions.

As MC can provide N- and C-rich substrates in a cost-efficient way, it appears promising for the use in regenerative agriculture. The farmers' interviews supported the results of MC being cost-efficient and practicable for on-farm composting. Nevertheless, the field application of compost can substantially increase the GHG balance of what at first sight appears to be a climate friendly composting process. Future studies need to further address this issue, as well as the impact of MC substrates on soil health.

Keywords: On-farm composting, Reductive composting, Regenerative agriculture, Microbial Carbonisation, Mikrobielle Carbonisierung, Greenhouse gas emissions

Zusammenfassung

Die Suche nach ackerbaulichen Lösungen für die Abnahme der Bodengesundheit, offene Nährstoffkreisläufe sowie Treibhausgasemissionen (THG) der Landwirtschaft, vor dem Hintergrund des drohenden Klimawandels, waren Motivation für diese Studie. Ein Kompostierungsversuch auf einem schwedischen Landwirtschaftsbetrieb sollte Antworten auf die übergeordnete Forschungsfrage liefern, wie praktikabel und klimafreundlich landwirtschaftliche Kompostierung mittels Mikrobieller Carbonisierung (MC) im Vergleich zur konventionellen Kompostierung (CC) ist. MC kann als biologische Umwandlung von Biomasse unter mesophilen und anoxischen Bedingungen verstanden werden, im Gegensatz zu CC, welchem ein aerober und teilweise thermophiler Abbauprozess zugrunde liegt.

Die MC-Methode wurde mithilfe natur- und sozialwissenschaftlicher Methoden untersucht. Es wurden Feldversuche durchgeführt, begleitet von Substrat-, Boden-, Emissions- und Porengas-Messungen, sowie Aufzeichnungen des Maschineneinsatzes. Darüber hinaus wurden Interviews mit Landwirten geführt, welche MC in Deutschland bereits anwenden, um einen besseren Einblick in die praktische Anwendung und die Bedürfnisse der Landwirte zu erhalten.

Die Ergebnisse deuten darauf hin, dass MC-Substrate nach der Kompostierung reicher an Stickstoff (N) und Kohlenstoff (C) als CC-Substrate sein können. Der Maschinenbedarf für MC betrug nur ein Zehntel von CC, was mit geringeren fossilen Emissionen einhergeht. Ein Novum war, dass zum ersten Mal Lachgas-Emissionen (N_2O) von MC gemessen wurden. Insgesamt waren die THG-Emissionen bei MC während der Kompostierung pro Tonne Kompost um 30 — 40 % niedriger als bei CC. Dieser Vorteil wurde jedoch durch 28 – 40 % höhere Emissionen (pro Hektar) auf dem Feld wieder ausgeglichen. THG-Bilanzen sind in hohem Maße von der Messmethodik, dem betrachteten Zeitraum und der Bezugseinheit abhängig, in der die Emissionen ausgedrückt werden. Da CC während der Kompostierung höhere N-Verluste aufwies, emittierte MC insgesamt 5 – 29 % weniger THG pro auf dem Feld ausgebrachtem kg N. Es war daher nicht eindeutig, ob MC oder CC in Bezug auf die THG-Emissionen besser abschnitt.

Wie auch durch die Interviews bestätigt wurde, liefert MC auf kosteneffiziente Weise N- und C-reiche Substrate und erscheint damit vielversprechend für den Einsatz in der regenerativen Landwirtschaft. Da die Ausbringung des Komposts jedoch die THG-Bilanz eines auf den ersten Blick klimafreundlichen Prozesses deutlich erhöhen kann, sollten künftige Studien sich mit dieser Problematik sowie mit den Auswirkungen von MC-Substraten auf die Bodengesundheit näher befassen.

Preface

Agriculture is feeding mankind since over 10.000 years and is constantly changing in the way it does so. Not only changes in climate, but also evolving agricultural practices and paradigms are shaping what is perhaps the most essential of all activities on which human civilization is built. These diversities and dynamics are what make agriculture so interesting for me, because it reveals the scope and prospects for a sustainable development.

In a time in which humanity has greater influence than ever before on its host planet Earth – namely the Holocene era – I believe it is our most fundamental task not only to preserve this place, but also to regenerate the damage we have caused. I am glad that I feel well educated to promote a positive change not only in agriculture, but also in the way society treats and understands nature.

The two-year study of agroecology has enhanced and broadened my holistic understanding of agriculture embedded in a societal and ecological environment. I was able to deepen the ability of perceiving a farm as an entity that interacts with its environment, which is crucial to finding the root causes of problems. In this sense, agroecology introduced "systems thinking" as a very helpful methodology to me. Coming from an agricultural science background, another important realisation for me during the study of agroecology was that traditional and practical knowledge need to be equally recognised as very important sources in a scientific context. To capture these multiple perspectives, an interdisciplinary understanding, mixed methods and participatory approaches seem to be gaining importance. The training in agroecology provided me with suitable skills for such challenging endeavours. Finally, my time at SLU and the casual and personal contacts with researchers and lecturers have given me valuable and low-threshold insights into international research and science.

My motivation to improve the sustainability of the food sector has found good company and a solid scientific basis in agroecology. During my studies, I came across the concept of regenerative agriculture, which puts many agroecological concepts into practice. Its emphasis on regenerating damaged ecosystems to increase their productivity and resilience, taking nature as role model, deeply impressed me. At the farm Biskopshagens Odlingar I began to experience what regenerative agriculture means in the larger context of arable production, and I am grateful for the indispensable time there which complemented my studies admirably. Understanding the needs of this farm on its journey to sustainability brought me to the topic of reductive composting, which I began to explore in 2019.

From delving into the theory, to initially gaining experience with composting on agricultural scales, to designing and conducting the accompanying research, this project required a lot of expertise and time. Doing all the field research myself meant spending midsummer sunsets on the compost heap and withstanding freezing winter winds in the field. Without the support I received from all sides I would never have been able to accomplish what I did. This extensive and multi-layered process meant that the completion of the work in part-time took until early 2022. However, I do not see this as a disadvantage. On the contrary, it has allowed for the inclusion and deepening of multiple perspectives and points of view. Persevering for about three years was a challenge, but one that I myself and the diversity of interpretation of the results have grown a lot from. And finally, writing such an extensive scientific paper in a foreign language was a challenge.

I am pleased, if I was able to bring forth a practically relevant outcome with this master thesis, based on scientific investigations of natural processes. Since this would not have been possible without a lot of cooperation and contributions from other people, in return I would naturally like to share and further develop the knowledge gained with other farmers and thus support the movement of sustainable and regenerative agriculture. This is what agroecology as science, practice and movement means to me.

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Abbreviations

AA	After aeration
BA	Before aeration
C	Carbon
CC	Conventional windrow composting
C_{tot}	Total Carbon
CO_2	Carbon dioxide
CO_{2-eq}	Carbon dioxide equivalents
CM	Chicken manure
CH_4	Methane
C/N	Carbon to nitrogen ratio
CS	Cereal straw
CU	University of Copenhagen
DM	Dry matter
EM	Emission (singular or plural)
et al.	Et alia
etc.	Et cetera
GHG	Greenhouse gas
GM	Green manure (ley)
GWP_{100}	Global warming potential, referring to an impact period of 100 years
H_2O	Hydrogen oxide (Water)
H_2S	Hydrogen sulphide
HM	Horse manure
LCA	Life-cycle-assessment
MC	Microbial Carbonisation
Mg	Magnesium (or mega gram as unit)
N	Nitrogen (or in statistical context referring to a quantity)
Na	Natrium
N_{org}	Organic Nitrogen
N_{min}	Mineral Nitrogen
N_{tot}	Total Nitrogen
NH_3	Ammonia

NH_4-N	Ammonium-Nitrogen
N_2O	Nitrous oxide
NO_3	Nitrate
O_2	Oxygen
OM	Organic matter
P	Phosphorus
PG	Pore gas (singular or plural)
PGC	Pore gas concentrations (singular or plural)
P/N	Phosphorus to nitrogen ratio
pH	*Pondus hydrogenii*
RA	Regenerative Agriculture
S	Sulphur
SOM	Soil organic matter
SLU	Swedish University of Agricultural Sciences
SMHI	Swedish meteorological and hydrological institute
TIFI	The individually focused interview
WC	Wood chips

Symbols and Units

° C	Degree Celsius
$	US-Dollar
%	Percent
ø	Average
∂	Change of a value over a certain period
µg	Microgram
∑	Sum
>	Larger than
<	Smaller than
a	Year
d	Day
g	Gram
h	Hour
ha	Hectare
kg	Kilogram
m	Meter
m^2	Square meter
m^3	Cubic meter
mm	Millimetre
Mg	Mega gram (metric equivalent to ton)
ppm	Parts per million
vol%	Volume percent

Definitions

Bioremediation

Bioremediation is the use of organisms (procaryotes, fungi, plants) for the biological detoxification of ecosystems (Kensa 2011). In the context of composting, this can be associated with the term *hygienisation*.

Compost suppressivity

“The ability of compost to generate an environment partially or totally adverse to the development of plant disease(s), although a pathogen might be present and the host plant is susceptible to it, is defined suppressivity” (Pane & Zaccardelli 2014, p. 153).

Compost tea

“Compost tea is a watery extract of microorganisms and nutrients from compost for application to the soil or crop canopy” (Evans & Percy 2014, p. 173). Compost tea can be applied as foliar application for phytosanitary purposes (see compost suppressiity) and as plant fortifier.

Hygienisation

In hygienised substrate pathogens and fertile weed seeds are absent (Haug 1993). Hygienisation of compost substrates can be achieved by thermal or biological means (Wonschik 2017).

Soil fertility

An early pioneer in soil fertility research, Hans-Peter Rusch, described soil fertility as a result of the living process *soil nutrition – soil tilth – rhizosphere – plant* and that it is not a material quantity but a biologically functional capacity (Rusch 1968). A more mechanistic understanding of Scheffer and Schachtschabel (2018) reduces the definition of soil fertitity to ***the capacity of a soil to serve as plant habitat.*** Mostly, this is reduced to *productivity* and thus the ability to produce yields. Soil fertility is determined by physical, chemical and – currently gaining more attention (Wall *et al.* 2019) – microbiological balances and conditions of the soil (Diepenbrock *et al.* 2009).

Soil health

Janzen *et al.* (2021) highlight the importance of the notion soil health as a metaphor and defines it as ***"the vitality of a soil in sustaining the socio-ecological functions of its enfolding land"*** (p. 1). Socio-ecological functions include: human well-being, cultural repository, aesthetics, biodiversity, habitat, climate buffering. Moreover, *soil quality* functions (air and water quality, erosion control) and *soil fertility* functions (yield, profit) are included in this definition. Other authors define *soil health* in a similarly holistic way, thus distinguishing it from productivity-centered terms, such as *soil fertility* (Lehmann *et al.* 2020).

Soil life

The term soil life describes the quality, quantity and interaction of fauna and flora in the rhizosphere, encompassing *bacteria*, *arachea* and *eucaryota* (like fungi, nemathodes, arthropodes, mammals and plants) (Scheffer & Schachtschabel 2018). A healthy soil life can be supportive for nutrient cycling, formation of soil structure, weed and disease suppression, C-sequestration, decomposition of plant residues, bioremediation (Ingham 2004; Trognitz *et al.* 2016).

Soil organic carbon (SOC)

SOC is the soil-C, present in organic forms, and is derived from living things such as plants, animals and microbes (Gilbert *et al.* 2020a).

Soil organic matter (SOM)

SOM is the SOC plus the hydrogen, oxygen and nitrogen that are part of the organic compounds. SOM (%) = SOC (%) x 1.72 (Gilbert *et al.* 2020a). Lehmann and Kleber (2015) emphasize that SOM needs to be understood as "a continuum of progressively decomposing organic compounds" and should replace the more untangible notion *humus*.

Substrate (Start- / End-)

The term "substrate" refers in this text to biomasses, which can either be composted (start-substrate) or have been composted (end-substrate).

1 Introduction

Omnipresent agricultural problems such as the decline of biodiversity and soil health[1], open-ended nutrient cycles, greenhouse gas (GHG) releases and the vulnerability of cropping activities to changing and more extreme weather conditions demand solutions (Lal 2011; Jones *et al.* 2012; FAO & itps 2015; IPES-Food 2016; Beckmann *et al.* 2019; Schwarzer 2019; Stuchtey & De Liedekerke 2019). Agriculture is a global sector that not only significantly contributes to exceed the earth's carrying capacity but is moreover heavily influenced by this disturbance (Dale 1997; Campbell *et al.* 2017; Poore & Nemecek 2018; Díaz *et al.* 2019; Willett *et al.* 2019). Moreover, society increasingly questions the sustainability of industrialised and agrochemical-based farming (Dahlberg 1994; IPES-Food 2016; IPES-Food & ETC Group 2021). Humanity is dependent on sustainable food production, both due to the need of healthy food and a way of production that promotes a healthy environment. Consequently, for a food system to become sustainable, all negative and previously externalised effects must be consistently included in the assessment to reveal which practices are truly sustainable. (Kremen & Miles 2012; Sanders & Heß 2019; Stuchtey & De Liedekerke 2019).

Some approaches which aim at transforming agriculture and the whole food system towards higher sustainability are well known. Agroecology is one of those concepts, with a holistic emphasis on practical, scientific, social and political perspectives (Wezel *et al.* 2009; Gliessman 2015). Another one is organic agriculture, which is already more institutionalized and has a hands-on approach of practices and set regulations (Pimentel *et al.* 2005; Sanders & Heß 2019). Both approaches have a lot in common and are relatively well established (Niggli 2015; Migliorini & Wezel 2017).

Sustainable development, defined according to the Brundtland report, is a development which meets the needs of the present without compromising the ability of future generations to meet their own needs (Keeble 1988). Especially with regards to food systems, this concept is recently being challenged by the notion regenerative agriculture (RA), which some authors suggest goes even beyond sustainability (Koerber 2018; Béné *et al.* 2019; Hermani 2020). Burgess *et al.* (2019) distinguishes between degenerative

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[1] See "soil health" under definitions.

agriculture (causes harm), sustainable agriculture (reduces harm) and regenerative agriculture (enhances). An example, of why the emphasis on sustainability might be criticized as being too narrow, is that many agricultural soils have already been degraded by unsustainable agricultural practices (Lal 2011; Jones *et al.* 2012; FAO & itps 2015) and therefore soil health must be regenerated before it can be sustained for future generations (Koerber 2018; Hermani 2020). Regeneration[2] and thus continuous improvement of soil health, biodiversity and other ecosystem services, is needed to reverse man-made damage and form a foundation for resilient and productive food systems, which can ensure food security under climate change conditions and even reverse it by sequestering carbon (C) (Jones *et al.* 2012; Rodale 2015; Burgess *et al.* 2019; Rosa-Schleich *et al.* 2019; Schwarzer 2019; Hermani 2020).

Even though the notion of RA already emerged in the 1980's in north America and regained much importance worldwide in the last five years, there is still a lack of a clear and universally valid definition, as Hermani (2020), Schreefel *et al.* (2020) or Giller *et al.* (2021) state in their recent literature reviews. Core ideas of RA are to produce agricultural products with high nutritional value, while at the same time regenerating and enhancing the agroecosystem functions (Rodale 2015; Burgess *et al.* 2019; Schreefel *et al.* 2020). The dependence of farmers on costly external inputs shall be reduced by mimicking nature with its diverse and productive ecosystems (LaCanne & Lundgren 2018). This is achieved by means of a broad set of principles and practices (Koerber 2018; Burgess *et al.* 2019; Hermani 2020; Schreefel *et al.* 2020), with the objective to enhance environmental, social and economic dimensions of sustainable food production (Schreefel *et al.* 2020).

The main objectives of RA – increasing soil life and sequestering C – are initially pursued through the principles of minimizing soil disturbance and fallow periods and thus maximizing photosynthetic productivity (Rodale 2015). Additional supply of organic matter (OM) and biological diversity, in form of compost, can moreover have substantial positive impacts on the regeneration of soil health (Kluge *et al.* 2008; FAO & itps 2015; Gilbert *et al.* 2020b) and natural pest management[3] (Pane & Zaccardelli 2014). Furthermore, composting waste biomasses can contribute to closing regional nutrient and C cycles by substituting other fertilizers and soil amendments and thereby reducing GHG emissions (EM) of cropping systems (Kluge *et al.* 2008; Boldrin *et al.* 2009; Erhart *et al.* 2015; Erhart *et al.* 2016). Therefore, applications of

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[2] "The term regeneration stems from the Latin *genero* (to produce, father, procreate) and *re-* (back or again) and refers to a process of rebuilding, restructuring and renewal. […] The discourse of regeneration does not focus on harm reduction, i.e. to do less bad, but on net-positive outcomes as a positive and empowering vision" (Hermani 2020, p. 41). See as well Burgess *et al.* (2019).

[3] See "compost suppressivity" under definitions.

compost and compost tea[4] are considered a RA practice (Rodale 2015; Koerber 2018; Burgess *et al.* 2019; Schwarzer 2019; Hermani 2020; Schreefel *et al.* 2020).

Since buying and applying externally produced compost can be costly at farm scale, on-farm composting can be considered as a good alternative (Rynk *et al.* 1992; Peigné & Girardin 2004). The potential advantages of on-farm composting, compared to buying it, comprise compost as affordable soil conditioner and fertilizer, a possibly saleable product, improved manure handling (reduced odours, EM, leaching, weed and pathogen pressure) and bedding for livestock (Rynk *et al.* 1992; Peigné & Girardin 2004; Maheshwari 2014; Grand & Michel 2020). On the other hand there are also possible drawbacks of composting on the farm, like time and money investments, land dedication for composting, difficulties of integrating the composting into operational procedures, a slow and sometimes hardly predictable release of nutrients in the soil, possible pollutions when contaminated material from outside the farm is used for composting (Rynk *et al.* 1992; Grand & Michel 2020).

There are numerous ways of composting. Conventional composting methods are mostly aerobic and thereby oxidising. Alternative approaches are reductive and therefore not aerobic. There is not yet much scientific literature on the latter, but some authors consider reducing conditions as particularly favourable for the objectives of RA (Husson 2012; Näser 2020). Reductive composts are thought to have a diverse microbial community composition and high C contents (Näser 2020). Some studies also report higher plant nutrient availability and greater biomass growth from reductively produced composting amendments (Wonschik 2017; Pandit *et al.* 2019). The following two subsections compare an aerobic and a reductive composting method, used in the present study.

1.1 Aerobic windrow composting (CC)

The term composting is defined as the decomposition and stabilization of OM performed by a diverse microorganism community (Wagner & Illmer 2004). During this process, heterotrophic microorganisms mineralise organically bound C and transfer minerals into plant-available forms (Wagner & Illmer 2004; Maheshwari 2014). As Wagner and Illmer (2004) summarize, many authors emphasize the importance of controlled aerobic, humid and temporary thermophilic conditions, under which the decomposition process takes place, and what distinguishes it from natural rotting. One of the most

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[4] See "compost tea" under definitions.

common and widespread open composting technologies is aerobic windrow composting, which in the following is referred to as conventional composting (CC).

To ensure the above-mentioned conditions, temperature (up to 70 °C) and water content (50–70 %) need to be controlled throughout the process (Peigné & Girardin 2004; Jiang *et al.* 2011). Factors, which influence these conditions are the substrate[5] composition, physical aeration and watering (Wagner & Illmer 2004; Jiang *et al.* 2011). Especially early during the composting process, in the thermophilic phase, when mineralisation rates are high, frequent aeration is required, to maintain aerobic conditions (5 – 15 vol% O_2) (Rynk *et al.* 1992; Wagner & Illmer 2004; Puyuelo *et al.* 2010). After having passed through the mesophilic (10 – 45 °C), thermophilic (> 40 °C), cooling down (ambient air temperature) and maturation (formation of stabile C-fractions) phases, the end-product is described as hygienic[6] and biostable with positive effects on soil fertility[7] (Peigné & Girardin 2004; Wagner & Illmer 2004).

During the decomposition process the substrate loses volume, weight and water, where mass-losses of 40 – 50 % are common (Epstein 1997). C degradation during aerobic composting of 40 – 70 % has been reported (Boldrin *et al.* 2009). Products of these decay and oxidation processes are mainly carbon dioxide (CO_2) and water (H_2O) but also other gases, such as ammonia (NH_3), methane (CH_4) or nitrous oxide (N_2O), which will mostly be lost as EM (Wagner & Illmer 2004).

Which EM and how much of them are released depends on variables like initial substrate composition, composting method, moisture content and aeration (Boldrin *et al.* 2009). Since CO_2 has a lower global warming potential (GWP) than N_2O and CH_4 and is moreover considered as biogenic EM, it is the targeted gas to emit (Myhre *et al.* 2013). It is not always easy to establish the right conditions for success, and moreover there is a controversy between authors about the optimal conditions in a compost to avoid other EM than CO_2 (Peigné & Girardin 2004; Jiang *et al.* 2011; Saer *et al.* 2013).

Next to the EM, generated through the decomposition process itself, geogenic EM from the use of fossil fuels for mechanical processing of the composts are intrinsic to most composting operations and are considered as the bigger EM source by some authors (Cadena *et al.* 2009; Saer *et al.* 2013). However, composting in general can not only produce EM but as well contribute to avoid EM by the substitution of other fertilizers or peat mining etc. (Boldrin *et al.* 2009; Erhart *et al.* 2015).

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[5] See “substrate” under definitions.

[6] See “hygienisation” under definitions.

[7] See “soil fertility” under definitions.

Overall, CC can be considered as a labour demanding process, associated with geogenic and biogenic EM, especially when conditions are not perfect. It is reasonable to assume that especially farms, that compost only on an incidental basis, have difficulties in controlling and creating the preferred conditions. Furthermore, the large loss of C during decomposition may limit the contribution of CC substrate to soil organic matter (SOM), compared to other composting methods. Under these circumstances it may be doubted that CC can be considered a best practice for regenerative farms. This is also because, under tough operational procedures with time constraints, it may be that the drawbacks outweigh the possible benefits in certain cases.

1.2 Microbial Carbonisation (MC)

The reductive composting method, called Microbial Carbonisation (MC) was first described by the German agronomist Walter Witte in two small books (Witte n. d.-a; Witte n. d.-b). A somewhat more profound and systematic description of the theory behind the method, including some biological and chemical explanations, can be found in the doctoral thesis of Wonschik (2017). According to Witte (n. d.-a) and Wonschik (2017) the term Microbial Carbonisation can be understood as the biological transformation of biomass under mesophilic and anoxic conditions into a substrate, containing nutrients, in both organic and inorganic plant-available forms, and biologically stabilized C. Anoxic (often confused with anaerobic) is used in this text in accordance with the definition of Liss and Baker (1994) as a condition in which no free oxygen is present but oxidised elements, such as nitrate, are available. Anoxic conditions are moreover defined by its redox potential ($E'0 > 0$) (Liss & Baker 1994). Since composting is often defined in a somewhat limited way by aerobic conditions (see 1.1), the term *reductive composting* will therefore be used in this work, following Näser (2020), in order to be able to define MC as a composting method. Due to the limited literature available in English, MC will be discussed in more detail below than CC was in the previous chapter, in order to make this rather unknown method more understandable to the reader.

In a recent presentation Witte (2021) emphasised that he does not want to be seen as the inventor of the MC method, but that “microbial carbonisation” is a self-organisation principle of nature and thus part of the evolutionarily developed action strategy of microorganisms, which will be described in the following. Crucial for the MC process are the right moisture (35 – 50 %) and temperature (up to 50 – 60 °C) conditions, and moreover a low (< 1 vol%) oxygen (O_2) pore gas content (PGC) (Witte n. d.-a). Witte (n. d.-

a) describes the right range of moisture as essential for providing enough water-film for bacteria to live. On the other hand, too much water would hinder the diffusive supply of pore gases (PG) which microbes need for respiration or as electron acceptors. Moisture content is regulated by the start-substrate composition and irrigation of the substrates. Temperature is also regulated by the substrate composition and by limiting the O_2 access into the compost through recompacting or sealing the surface (Wonschik 2017; Witte n. d.-a).

The above described mesophilic milieu is in particular needed as suitable habitat for *Bacillus subtilis*, which is described as a major player within the MC process (Wonschik 2017) and composting in general (Phae & Shoda 1990). This bacteria, as well known as the “hay-bacillus”, is abundant in topsoil layers and on the stem bases of grasses (Stein 2005; Näser 2020). Hence *Subtilis* is introduced to the compost by the substrate itself or can be added, dissolved in water, as a hay infusion (Wonschik 2017). The metabolites produced by *B. subtilis*, such as hydrolases, cellulases and chitotriosidases, contribute to solubilizing the biomass (Stein 2005; Castillo *et al.* 2013; Wonschik 2017).

C-fixation pathways in MC

In contrast to CC, MC does not aim at reducing the biomass by oxidation of C but is rather based on the assumption that C is stabilised in the substrate. Stabilization of C is achieved in MC by the means of *complexation* (Bolan *et al.* 2012), *chemolithoautotrophic* CO_2*-fixation* (Shively *et al.* 1998; Kirchman 2011), *carboxylation* (Nakano & Zuber 1998) and *anoxic methanotrophism* (Kang *et al.* 2021).

Complexation describes the formation of organo-mineral complexes that make organics unavailable for decomposition and can be facilitated in MC by the addition of clay minerals as ion-acceptors (Bolan *et al.* 2012) in the beginning of the composting process (Wonschik 2017).

Seven different pathways are known for the second C-fixation pathway, *chemolithoautotrophy* (Lafferty 1963; Shively *et al.* 1998; Hügler *et al.* 2005; Scott & Cavanaugh 2007; Berg 2011; Figueroa *et al.* 2018), while the Calvin-Benson-Bassham cycle is considered to be the most widespread among them (Zhao *et al.* 2020). Various microorganisms such as proteobacteria or archaea have the ability to fix CO_2, and Lafferty (1963) describes CO_2 as essential growth factor for *B. subtilis* under anoxic conditions.

The energy needed for CO_2-fixation is delivered by different processes: Witte (n. d.-a) considers H_2O, which is split by cyanobacteria on the surface of the heap (sun-radiation induced photolysis) as greatest H^+ source. Moreover, NH_3 and hydrogen sulphide (H_2S) seem to play important roles as energy donors (Scott & Cavanaugh 2007; Witte n. d.-a). Witte (n. d.-a) suggests the following reaction formulas for CO_2-fixation:

$$6\ CO_2 + 4\ NH_3 = C_6\ H_{12}\ O_6 + 2\ NO_3 + 2\ N_2$$

$$6\ CO_2 + 12\ H_2S = C_6\ H_{12}\ O_6 + 6\ H_2O + 12\ S$$

Nitrate, resulting from the first reaction, can be further utilised as electron acceptor by the class of *Bacillus* to bind nitrogen (N) (Nakano & Zuber 1998; Castillo *et al.* 2013). The second reaction shows how possible odour EM from H_2S can be minimised. This is additionally supported by sulphide oxidation of proteobacteria (Muyzer & Stams 2008; Witte n. d.-a). Thus, sulphur (S) as a waste product of chemosynthesis explains the sulphur coagulations that can be observed in MC heaps (Witte n. d.-a). Witte (n. d.-a) also highlights the reactivity of free S, which forms stabile bounds with heavy metals to form sulphides. This puts these out of action as plant-toxic substances.

By means of *carboxylation* – under anoxic conditions that force *B. subtilis* and associated microorganisms into the fermentation metabolism – glucose can be converted into carboxylic acids, such as lactate (Nakano & Zuber 1998; Wonschik 2017):

$$C_6\ H_{12}\ O_6 = 2\ C_3\ H_6\ O_3$$

Furthermore, the reduction of CO_2 by *carboxylation* is mentioned by Witte (n. d.-a) as process critical, whereby methanoic acid (an important chemical intermediate) is produced:

$$2\ NADPH + CO_2 = 2\ NADP + C\ H_2\ O_2$$

To facilitate such C-fixation processes, high concentrations of CO_2, NH_3, H_2S and CH_4 are considered beneficial (Witte n. d.-a). This is confirmed for CO_2 by recent studies (Steffens *et al.* 2021) and Kang *et al.* (2021) emphasize the important role of anoxic CH_4-oxidation by methanotrophs in the global CH_4 cycle. To ensure that the gases can be metabolized within the MC heap and are not emitted, the surface must be sealed by physical compaction or alternative methods, like slurry application (Wonschik 2017; Näser 2020).

Hygienisation in MC

Contrary to the conventional doctrine that hygienisation[8] can be achieved only through high temperatures (like in CC), Wonschik (2017) showed in phytosanitary trials that in MC hygienisation is sufficiently achieved by biological processes, since suppressive microorganisms colonise especially under mesophilic milieu conditions (Hoitink *et al.* 1997; Idelmann 2006). For instance, *Bacilli* have the ability to excrete antibiotics and produce extracellular enzymes that decompose polysaccharides and nucleic acids (Asaka & Shoda 1996; Stein 2005; Castillo *et al.* 2013). In that way, they contribute to the inhibition of phytopathogenic microorganisms (Phae *et al.* 1990; Phae & Shoda 1990; Idelmann 2006). Liss and Baker (1994) describe, in addition, that

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[8] See "hygienisation" under definitions.

some pesticides and other hazardous compounds only decompose under anoxic or anaerobic conditions and would persist under aerobic conditions.

Agronomic implications

Wonschik (2017) found higher levels of ammonia (NH_4) and nitrate (NO_3) in MC compared to CC, which can be interpreted as either improved fertilization effect or risk for leaching-losses. Growing trials showed three times higher biomass growth of maize when grown in MC substrate, compared to CC (each mixed 1:1 with loamy soil). Wonschik (2017) concluded that the significantly higher C contents of the MC substrate could have acted as C reservoir which might have resulted in CO_2-foliar-fertilization in addition to the greater N-fertilisation effect.

Witte (n. d.-a) and Wonschik (2017) are in agreement that the C-efficiency of MC end-substrates is very high (90 % of the initial C remains, compared to 40 – 60 % in CC). The high C contents of MC substrates bear the potential of enhancing soil fertility but, to the author's knowledge there are no studies to date that investigate how MC substrates behave in terms of GHG release and C-retention when applied on agricultural fields.

Measured only during the composting phase, Wonschik (2017) showed that MC emitted significantly less GHG compared to CC. However, it must be mentioned that an insufficient and not very transparent description of the EM measurement methodology limit the reliability of the results of Wonschik (2017). Furthermore, only CO_2 and CH_4 were measured. Furthermore, N_2O as a GHG with high GWP (Myhre *et al.* 2013) was not taken into account.

Wonschik (2017) found that the demand for labour, machinery and energy is 20 % lower for MC than for CC, resulting in the economic superiority of MC. Ökoring (2019) came to similar conclusions about the labour demand.

Further research implications

To the knowledge of the author there is only one more scientific work about MC available, resulting from a master thesis (Binner *et al.* 2019; Egger 2019). Unfortunately, the contribution of Egger (2019) is limited with respect to MC, as the implementation contained obvious deviations from the method, which have not been mentioned in the publications.[9]

Next to the before mentioned scientific publications there was a non-scientific research project implemented between 2015 – 18 in north Germany, specifically looking at the advantages and disadvantages of the practical application of CC versus MC on farms (Ökoring 2019). Since 2019 another

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[9] The most obvious methodological flaws, made by Egger (2019): heavy compaction of the MC heap might have caused anaerobic conditions, what would not represent MC's anoxic conditions; the surface was possibly not properly sealed, which might have favoured the release of gases; very unusual start-substrate composition and no adequate crushing are limiting the subjective significance; EM measurements from only one single day do not allow for an encompassing assessment.

on-farm research project is running that compares the effects of different composts on soil fertility in Germany, one of which is MC (Hülsbergen 2021). Very recently and with a similar approach, a new research project was started by Walter Witte, in collaboration with a large-scale farm in Germany to examine MC in the context of climate change, environment and sustainable agriculture (dvs 2021).

The limited number of available publications to date motivates to conduct more scientific work on this topic – especially as farmers and extension services demand more reliable information on MC and its potential as most likely climate-friendly on-farm composting alternative (Hämmerli 2018). Considering the potentials mentioned above, MC seems to be an interesting research object in the RA context. Furthermore, the unknown or uncertain details regarding GHG EM from MC composting and field application of MC substrates motivate this research.

1.3 Design and outline of the study

According to agroecological systems thinking the approach of this thesis is to investigate the MC method by the means of both natural and social science methodologies (Sinclair *et al.* 2019). Field trials were conducted, to evaluate different aspects of the method – accompanied by a diverse data collection, including substrate, soil, EM, and pore gas concentration (PGC) measurements, as well as records of machinery use. In addition, interviews were conducted with farmers already using MC in practice, to gain a better insight into its practical application and the farmers' needs. With this multi-faceted set of observations, it is possible to draw a more holistic picture of the research object.

Following the call for a sustainable and regenerative food system this thesis aims at examining the potential values of reductive composting for on-farm application, in comparison to aerobic composting. The research object here is MC, which is the only reductive method that has been specifically described and defined in the scientific literature so far. Leading motivation for conducting this research was the following question: How feasible and climate friendly is on-farm composting with MC for the purpose of substituting external fertilizer inputs and contributing to SOM increase?

This thesis aims at some novelties: N_2O, as one of the strongest GHG, is for the first time measured on MC; moreover, the prolongation of the measurements into the field application phase most likely enables to assess the stability and climate impact of the different compost substrates in a better way than just looking at the actual composting phase. Undertaking both steps was considered important because yet no previous study about MC did so. Therefore, the following hypotheses were tested:

1. Under farm conditions and with existing farm machinery, MC delivers a kilogram of N with less machinery labour than CC.
2. MC releases less GHG (N_2O, CH_4, CO_2) than CC during the composting process and during the first 11 weeks after field application.
3. MC end-substrates contain more total C and larger fractions of insoluble C than CC end-substrates.

Integrating perceptions of farmers on their own ways of implementing MC is most likely another novelty for such a natural science dominated on-farm study. Therefore, interviews were conducted with the aim of finding answers to the following research questions:

1. What is the motivation of certain farmers to do on-farm composting and why have they decided to use the MC method?
2. How do farmers adapt the MC method differently on their farms and which difficulties do they encounter?
3. Where are there gaps in knowledge about MC and in which areas is there a need for further research?

2 Materials and methods

2.1 The farm case

The natural science field experiments were carried out at the farm Biskopshagens Odlingar. The farm site is located in south-west Sweden (55°40'39.8"N 13°12'14.5"E), 17 m above sea level (Satellitkarta.se 2021) with a usual annual mean temperature of about 7 °C and precipitation about 800 mm (SMHI 2021). In the reference period of 2020 the annual mean temperature was 10.6 °C and precipitation 633 mm (SMHI 2021). The farm works according to organic standards, following the Swedish KRAV regulations (KRAV 2019). Beyond that the farm aims at implementing RA practices in arable and vegetable cropping to regenerate soil health and especially increase SOM.

Since there is no considerable number of livestock on the farm the need of importing organic (N) fertilizer is high. Processed and organically certified fertilizers are mostly expensive and have only limited positive effects on SOM and soil life (Jones *et al.* 2012; Jacobs *et al.* 2018). Moreover, a difficulty in fertilization-management of KRAV-certified farms are the restrictions on P application (KRAV 2019). This limits the usually used chicken manure (CM), which contains about 5 – 6 kg P Mg^{-1} dry matter (DM). The farms motivation to participate in this research project was therefore to find a way to gradually replace P-rich CM and other expensive fertilisers, while still ensuring sufficient N fertilisation. This should preferably be achieved with little time and money investment and the OM supply to the soil should be improved.

2.2 Experimental setup and procedure

The field trials were carried out under realistic farm conditions, for which reason only on the farm available infrastructure and machinery was used. This represents a limitation on the one hand, but on the other it is representative for how average farms would possibly implement on-farm composting. The project comprised two phases: in a first step the start-substrates were composted using different composting methods and in a second one the composting end-substrates were applied to a field.

2.2.1 Start-substrate composition and preparation

Two MC heaps (MC1 & 2) were compared with one CC windrow only due to resource constraints. Two MC variants were created on the one hand to observe the influence of different substrate components and on the other hand to have two chances to facilitate the MC process as successful as possible. Due to field conditions the composition of the CC compost was chosen to be the average of both MC treatments as described in **Table 1**. A third MC heap (MC3) was created later with different substrate composition than the first ones (see 2.2.2).

The first step was the preparation of the substrates: wood chips (WC) were watered on 18th of May, to let it absorb some moisture, before being mixed with other substrates. Horse manure (HM) was fetched from a neighbour on 20th of May (chemical analysis in appendix, **Figure A 6**). On May 26th chicken manure (CM), which was delivered to the farm already some weeks earlier, was soaked in water to about 90 % water content (chemical analysis in appendix, **Figure A 4**). This was done, following the advice of Walter Witte, to possibly transform most of the uric acid (which otherwise could harm the microbial community in MC) into ammonium and similar compounds. Green manure (GM) was harvested on 30th of May, after one day of drying on the field (after cutting) (chemical analysis in appendix, **Figure A 5**).

All substrates were mixed with the shovel of a telescope loader, according to the desired proportions of MC1 & 2 (**Table 1**). The mix MC1 was watered with about 2 m^3 since the moisture initially was only about 20 – 40 %. MC2 was watered with 0.5 m^3 only, since the moisture was found to be already around 50 – 60 %. Witte (n. d.-a) advises to use rainwater to avoid any input of biologically harmful substances (chlorine etc.) from community water. Since rainwater was not available in the needed amount, groundwater from the farms well was stored in open 1 m^3 containers for two weeks before use.

The mixes were set up to irregular lose heaps of about 3 m height, using a wheel loader, and left for the so-called maceration process on bare ground. Maceration is done for the purpose of cell wall destruction, moisture equalization and reproduction of micro life (log-phase) (Wonschik 2017; Witte n. d.-a). Temperatures were monitored during the maceration period until they reached almost 60 °C on the fourth day four and the substrates were further processed.

Table 1: *Start-substrate compositions [vol%] of MC1 – 3 and CC. HM: horse faeces and cereal straw CM: faeces from laying, GM: ley cuttings (grass and clover) harvested at BO, WC: branches from broadleaf trees chopped to about 60 mm, CS: cereal straw, pre-rotted.*

	MC1	MC2	MC3	CC
Horse manure (HM) [vol%]	55	55	–	55
Chicken manure (CM) [vol%]	32	19	25	26
Green manure (GM) [vol%]	–	13	10	6
Wood chips (WC) [vol%]	13	13	–	13
Cereal straw, pre-rotted (CS) [vol%]	–	–	65	–

2.2.2 Setting up and management of the compost heaps

After the maceration the substrates were loaded onto a tractor trailer by wheel loader and transported to a concrete floor, where the MC1 & 2 and CC heaps were set up on the 5th of June 2020. The concrete plate measured 12 m in length and 7 m in width. Within the south third in length a 2 m high concrete wall was set up over the whole width of 7 m on which the MC heaps were put against from both sides (see **Figure 1**). This design gave the opportunity to decrease the surface-volume relation of the heap, because the surface of MC heaps is prone to dry out and thereby release gases. For further protection against wind and sun, strawbales were placed on the west and south side of the concrete floor[10]. MC1 was partially shaded by a nearby tree over midday. The CC heap was placed at the north end of the plate to be accessible with the wheel loader for aeration from three sides.

The MC heaps were set up by dumping the substrate from trailer on the concrete. Hay was soaked in stale groundwater for at least 30 min to produce the hay infusion (hay-tea) for the inoculation of the substrate with *Bacillus subtilis*. About 2 L m^{-3} were applied in several portions manually with watering cans while dumping the material. After gently shaping the heaps with the wheel loader (without causing compaction), additional 45 L were applied on each MC heap's surface. The surfaces were gently compacted with a custom-made metal plate (2.0 x 1.6 m), which was fixed on the mounting of the wheel loader's arm. The heaps were about 1.6 m high and measured 6 m in length at the bottom and 3.9 m (MC1) and 3.5 m (MC2), respectively, in width. The shape was like a rectangular truncated pyramid. During the composting period, on 9th of June and 2nd of July both MC1 & 2's surfaces have each been inoculated with 2 and 35 L of hay-tea, respectively, to foster microbial development.

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[10] Witte (n. d.-a) advises to start the MC process in spring or autumn, when sun radiation is not at its strongest or lowest range. Moreover, he advises to place the heaps in partial shade.

The CC heap was loosely set up in a 6 m long, 0.9 m high and at the bottom 1.5 m wide windrow, without compacting the surface. The substrate mix consisted of the residual material from the MC heaps in a ratio of about 1:1.

A third MC heap (MC3) was set up on 15th of June, on grassland, with a different substrate composition than used for the other composts (Table 1). With estimated 60 m^3 this heap was almost twice the size as MC1 or 2. The general steps of substrate pre-treatment were like in MC1 & 2, but maceration took 6 days until the heap warmed up to 55 °C.

***Figure 1:** The composting site. In the front right-side CC, left MC1 & 2 with concrete wall in between and scaffold for performing the emission (EM) measurements on top. Strawbales for wind protection around the MC heaps against the main wind direction south-west. The picture was taken on 2nd of July 2020.*

2.2.3 Compost application to the field

On 22nd of September all four heaps (CC, MC1, MC2, MC3) were opened up with the wheel loader for sampling (see 2.315) and 10 t ha^{-1} of compost were then applied to a harrowed but unfertilized field (55°40'59.1"N 13°12'10.5"E), in four strips of 1 m width and 6 m length. The compost was incorporated manually with a rake to a depth of 0.03 m deep. On the next day winter wheat (WW) was seeded with a seeding rate of 240 kg ha^{-1} on the whole field at a depth of about 0.04 m. The soil type of the field was a boulder clay with a silt loam texture above carbonate rich sedimentary bedrock (SGU 2021) with 2.4 % SOM (see Figure A 1).

2.3 Compost-substrate sampling and analyses

The individual start-substrates (CM, GM, HM) and the mixtures (CC, MC1, MC2, MC3) were analysed at the start and end of composting to examine how their properties might change during decomposition. Taking a representative sample from non-homogeneous composting substrates can be difficult. Therefore, every sample consisted of a minimum of five subsamples which were taken from different locations of the substrate heap. Care was taken to collect the samples from random places and different depths of the heap and to obtain a visually representative sample compared to the heterogeneous whole.

2.3.1 Chemical analysis

The collected sample was thoroughly mixed in a bucket and a small subsample was taken to be send to the laboratory Eurofins (www.eurofins.com). Each sample was analysed for DM, ash, pH, C, N, P, K, Mg, Na and S content; according to EU 152/2009 for DM, ash and N and according to DS 259:2003, DS/EN ISO 11885:2009 for P, K, Mg, Na, S.

2.3.2 Carbon fraction analysis

Additional subsamples were dried, weighed and coarse ground (2 mm particle size) in the laboratory at SLU Alnarp, using a Retsch SM200 cutting mill. Van Soest analysis was carried out with these samples later on in the laboratory Artemis in France (www.artemislaboratoire.com) to give indications about the different C-fractions in substrates (Soest & Robertson 1979; Liyama *et al.* 1994). In this analysis, substrates were treated with different detergent solutions (Soest & Robertson 1979; Soest & Wine 2020), according to the following standards: NF V18-101 (1977) for ash, AOAC 991.43 for fibres insoluble and soluble (AOAC 1995), NF V18-122 for Neutral Detergent Fibre (NDF), Acid Detergent Fibre (ADF) and Acid Detergent Lignin (ADL) (AFNOR 2013). The fractions were interpreted as follows: ADL equals lignin, cellulose comprises ADF minus ADL, hemicellulose comprises NDF minus ADF, soluble components comprise everything but ash and NDF.

2.3.3 Total carbon and nitrogen analysis

Shares from the coarse ground subsamples were used to analyse total C (C-tot) and total N (N-tot) contents. Therefore, each sample was milled (< 10 µm) in a planetary ball mill (Retsch PM 400) and sub samples of about 3.00 Mg (± 0.17) were weighed into tin capsules. The analysis was carried out at the department of Geosciences and Natural Resource Management at University of Copenhagen (CU) in Denmark, on an elemental analyser (Flash 2000, Thermo Scientific, Bremen, Germany).

2.4 Soil sampling and analysis

Eight sub-samples, randomly spread over an area of about 200 m^2 around the chosen plot for the field trial, were taken on 25th of September 2020 and thoroughly mixed in a bucket. The samples were taken with a spade in 0.0 – 0.2 m soil depth. Stones and bigger plant residues were removed before 500 g of the fresh sample were sent to the laboratory Levende Jord in Denmark (www. levendejord.dk). The sample was analysed in the accredited lab (ISO / IEC 17025:2017), according to their standards.

The Albrecht analysis was chosen as methodology for analysing the soil properties, since it allows for a quite detailed insight into the soil chemistry. Not only nutrient contents but as well nutrient content ratios are indicated in this analysis, based on the cation saturation concept (Kinsey & Walters 2014).

2.5 Temperature and moisture measurements

Temperatures and moisture content in composts and the field were measured, using a wireless system of sensors from the company Sensmore (www.sensmore.se), which logged data every 30 min. To reduce the amount of data series, daily means were calculated afterwards for some data, since values were not frequently altering anyway. Digital soil thermometers (RT-1) for temperature and volumetric water content (VWC) sensors (ECH_2O EC-5) for moisture were used (www.metergroup.com).

During the composting period temperature and moisture data was logged in MC1 & 2 (about 0.50 m below surface). For MC3 and CC only temperature sensors were used. During field application soil temperature (in 0.15 m depth) and moisture (in 0.07 m depth) were logged.

2.6 Meteorological data

Air temperature, air pressure and precipitation data was retrieved from the Swedish meteorological and hydrological institute (SMHI), using the closest local weather station “Lund 53430“ (55°41'35.5"N, 13°13'30.4"E, 26.4 m above sea level) (SMHI 2021).

2.7 Emission measurements and analysis

2.7.1 Emission measurements

Three manual static non-steady-state (NSS) chambers per treatment were used to measure CO_2, CH_4 and N_2O EM from both composts and soils. Rochette (2011) elaborates on the various advantages of NSS – especially for the adequate measurement of N_2O, which was a focus of this study. In the awareness of the international discussion on NSS chamber methodologies, regarding comparability of N_2O results (De Klein *et al.* 2020b) and to minimise negative biases, the used measurement setup was similar to Rochette (2011).

The chambers were constructed from white compound polypropylene double layered sandwich sheets of 0.05 m thickness. On the inside they measure 0.57 x 0.57 x 0.60 m. To avoid leakage during measurements the chambers were placed on stainless steel collars. The collars were inserted into the ground (or compost) about 0.2 m and have a channel on the upper end, filled with water, to ensure airtightness between chamber and collar. The effective chamber volume needed to be calculated for each measurement, since it depends on the exact insertion depth of the collar and soil-, or compost-microtopography. Even though Rochette (2011) describes 0.2 m insertion depth as the minimum depth to avoid leakage in loose soils, this depth could unfortunately not be achieved during all compost measurements. (Minimum insertion depth in this experiment was 0.1 m.) Each chamber was equipped with a battery driven axial fan on the inside. On the top part of the chamber there was a 300 mm long spiral vent tube (inner ø: 4 mm) to compensate for tentatively changing pressures in the chamber during measurement but minimise ambient air intake (Rochette 2011).

Sampling was done using a Parker's CTS micro diaphragm pump (E134-11-120) that circulated air between the chamber headspace and a 20 ml glass vial for 1 minute. During the measurement period the performance of the pump was checked with a flow meter irregularly. Two samples were taken from each chamber on every measurement occasion: the first sample (T1) was collected after 1 min and the second sample (T2) after 31 min of closing the chamber for composts and 41 min for soils, respectively. The different closing times were reasoned in the assumption of lower gas fluxes from soils than from composts.

Following the recommendation of Rochette (2011), closing times were chosen relatively short, because small fluxes of CH_4 and N_2O should be captured. For the much larger fluxes of CO_2 this was most likely too long, resulting in a saturation effect in the chamber, what could lead to underestimation of those fluxes.

When the gas samples were sorted for shipment to the laboratory, a standard sample of atmospheric air from a gas cylinder (0.418 ppm CO_2, 0.334 ppm N_2O, 1.890 CH_4) was added before and after each batch of samples (one batch comprised one measurement occasion) to test the integrity of samples and their analysis (Rochette 2011). Analysis was carried out at University of Copenhagen (CU), using a gas chromatograph (GC) HP7890A (Agilent, Wilmington, USA) with electron capture detection for N_2O and flame ionization detection for CH_4. CO_2 was analysed as CH_4 upon nickel-catalysed reduction (methaniser).

2.7.2 Emission data analysis

Daily gas fluxes were calculated from T1 and T2 measurements for each gas (CO_2, CH_4 and N_2O), according to the ideal gas law, and expressed in g Mg^{-1} d^{-1} for the compost and g ha^{-1} d^{-1} for the field. Cumulative fluxes over the measurement period were calculated from daily flux values, using linear interpolation. For converting CH_4 and N_2O EM into CO_2-equivalents ($CO_{2\text{-eq}}$), global warming potential (GWP) factors of 27.2 and 273.0, respectively, were used (IPCC 2021).

To be able to express a flux per mega gram (Mg) of compost it was assumed that the substrate weighs 750 kg m^{-3}. Since unfortunately the specific weight of the substrate was not verified gravimetrically during this experiment, this assumption had to be based on literature values (Schaub-Szabo & Leonard 1999; Zemánek 2002; Khater 2015), in accordance with experiences from farmers who apply MC[11]. Composting and field EM can be summed up under the condition that 10 Mg ha^{-1} of compost were applied to the field.

In the scope of this thesis no statistical evaluation of differences between treatments could be performed, since analyses of variance (ANOVA) would have not been appropriate with non-randomised plots.

2.8 Pore gas measurements

A portable gas measurement device (X-am® 7000), produced by the company Dräger, was used to measure PGC in the compost heaps. The same measurement device was used by Wonschik (2017). Different kinds of sensors have been used to measure the following gases: electrochemical sensors for O_2 (DrägerSensor® XS R O_2 LS), H_2S (DrägerSensor® XS R H_2S) and NH_3 (DrägerSensor® XS NH_3); infrared sensors for CO_2 (DrägerSensor® Smart IR

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[11] Analysis results from two farmers, interviewed during this study, show densities of 811 and 850 kg m^{-3} with 32 and 33 % DM, respectively. In the present research DM content in MC was about 10 % higher (**Table 2**).

CO_2 HC) and CH_4 (DrägerSensor® Smart IR Ex). Two different lengths of lances (0.65 m and 1.5 m) were used to extract PG out of different depths. The lances are hollow with wholes at both ends. The end with a handle is connected by a hose with an integrated silica gel moisture filter to a pump.

Since the device shows real time gas concentrations, which can change substantially during short periods of time, a standardized procedure was applied. After 3 min of suction the gas concentration was found to be stable in most cases. Therefore, the value after 3 min was taken as record.

Measurements are snapshots from single spots, without repetitions. The lances were inserted from the side into the heaps with a slight 20 ° angle downwards. The short lances were inserted at 0.9 m height, the long lances at 1.2 m above ground. In CC only the short lance could be inserted due to limited size of the heap. CC measurements were replicated with one repetition from the opposite end of the heap, an average was calculated afterwards. In CC measurements were performed before and partly as well after aeration happenings (1 – 67 min, mean: 18 min after end of aeration).

To examine possible correlations between single PG and the relation of EM and PG the data was analysed, using Kendall tau test in IBM SPSS. This test was chosen as alternative to the more common Pearson test, because the data did not fulfil its formal preconditions.

2.9 Qualitative data collection & analysis

The qualitative part of the study is based on interviews with farmers, who already apply MC on their farms. Relevant interviewees were searched through private networks and social media in German speaking countries. Such a choice was considered appropriate as the MC method originated in Germany and is most common there (e. g. the lack of literature in other languages supports the assumption that experiences as well as the practical applications are most likely to be found in this region). A general call for an interview about experiences with MC was communicated in early 2021 via postings in topic related social media groups. Direct email inquiries were also sent to relevant farmers, who were known from private networks. A total of nine people replied that they were available for an interview. Seven interviews were finally conducted between January and March 2021. All interviewees fulfilled the inclusion criteria of having experimented with MC for at least two years.

2.9.1 Interview method and implementation

In order to cover as many voices of farmers as possible, yet implementing this in a time efficient way, the individually focused interview (TIFI) was chosen as methodology. This method has been developed by Clausen (2012) with the aim to provide a scientific methodology for qualitative research interviewing which avoids the common time and resource costly audio transcriptions, however without affecting reliability, validity, and transparency. Such an approach is additionally supported by Halcomb and Davidson (2005), who argues for the superiority of written field notes to verbatim audio transcriptions.

Very close to the approach of Clausen (2012), concept and procedure of TIFI was applied in four steps as follows:

1. Thematization, design and planning

An interview guide with themes and sub questions was designed (see **Figure A 8**). The interview guide was slightly adjusted after the first interviews being conducted, all in order to favour the conversation flow. Themes were a general site description, secondly general questions about on-farm composting and MC and thirdly specific details of the individual on-farm MC application.

2. Thorough introduction to the interview method

An introducing document was sent to the interviewees in advance of the interview (see **Figure A 9**). This was done with the aim of assisting the interviewee in preparing for the interview, the planned themes, the procedure and circumstances.

3. The interview and simultaneous writing of notes on statements

Each interview was planned to take about 30 minutes up to 1 hour time and being either conducted via telephone, video call or in person. During the interview the interviewer took notes of main statements. In agreement with the interviewee the interview was additionally recorded.

4. Writing of the summary draft and further joint production

After each interview a written summary was prepared by the interviewer. Since only one person conducted all interviews and wrote the summaries bias was expected to be minimized. The written summary was done by reviewing the notes and listening to the audio recording once again. Details were added to the statements, phrasing was altered to make statements more comprehensive, and notes were more thoroughly sorted according to the themes. An important step in TIFI methodology is the feedback loop, to validate the accomplished data. As soon as possible after the interview each interviewee got a summary draft sent via email, with the request of reviewing it, correcting and confirming the statements. The text was used for analysis after final approval of the summary by the interviewee.

2.9.2 Interview content analysis

Content analysis is not clearly to be separated from the interview method itself in the case of TIFI, mainly due to the initial analytical steps (e. g. structuring and explication) which were already carried out in phase four. In general, the analysis of interviews was grounded on the content analysis method of Mayring (2010). The interviews, which were already structured by the set themes, were juxtaposed and compared in an excel sheet. By means of inductive coding, categories were formed, guided by the farmer's statements for each theme. Based on the categories formed, comparisons were made between the interviews and conclusions were drawn. In this last step of the analysis translation of the content from German to English language was performed.

2.10 Work-economic data collection

Machinery labour hours spent on composting, were recorded in the field, and then divided by the estimated amount of substrate per treatment, to obtain the hours spent per m^3 or Mg of compost start-substrate. In the absence of gravimetric tests, the same density was used as in the EM calculation (750 kg Mg^{-1}, see 2.7.2). A total start-substrate amount of 53 m^3 (40 Mg) was estimated, distributed to MC1 with 24 m^3 (18 Mg), to MC2 with 22 m^3 (17 Mg) and to CC with 7 m^3 (5 Mg). To evaluate the machinery labour efficiency of MC and CC per kg N, the machinery labour input has been multiplied with N_{tot} values, retrieved from the substrate analyses.

Tasks, which were included in the calculation of machinery hours, are the substrate transport (from the place of collection to the final place of composting), setting up of the compost heaps and aerating CC with the wheel loader. Timespans of aeration events were calculated, including travel time with the wheel loader to the composting site, which corresponds to realistic on-farm conditions.

3 Results

The results are presented in four subchapters, which follow the chronological sequence of the study phases. The first part (3.1) deals with the measurements during the composting phase, the second part (3.2) shows the results gained during the field application phase. 3.3 focuses on a synthesized view of the total GHG EM from the composting and field application. Afterwards, in 3.4, the results from the survey of farmers are presented.

3.1 Part one: Composting

3.1.1 Temperature, moisture and visual observations

Together with moisture and temperature records, observations which may have been influential to the composting process are mentioned in the following. Mean air temperature during the composting period of 79 days was 18 °C and precipitation sum was 178 mm.

During the maceration process a day with precipitation of 10 mm has been experienced. Additional 14 mm rain fell just before the substrates were moved to the final composting place on 5th of June (**Figure 3**). This wet start of the composting period caused, that brown water was standing on the concrete plate and all composts (MC1-3 and CC) looked very wet on 7th of June. The following period, until the end of June, was dry and warm. On 16th of June, MC1 & 2 looked very dry in the surface and started to get bigger cracks on the surface. CC smelled bad and showed white mould on the surface.

Heap temperatures in MC1 & 2 continuously increased slightly during the first 3 – 4 weeks of composting (**Figure 3**). MC1 started with 44 °C and the temperature continually increased until the middle of August, where it stabilized at around 54 °C until the end. MC2 showed higher average temperatures than MC1 (**Table 5**). With 51 °C it already started off slightly warmer, reached its climax in the first days of July (61 °C) and stayed on this level just below 60 °C until the end.

The moisture level of MC1 started at 42 % H_2O and increased until the end of June (climax: 47 % H_2O). After this peak the moisture slightly decreased, until the measurements unfortunately stopped in the end of July at 41 % H_2O. The average moisture level in MC2 was found to be higher than in MC1 (**Table 5**). It rapidly increased from 30 % H_2O to 49 % H_2O within the first week. A continuous increase followed until it levelled off in the end of August at around 59 % H_2O (**Figure 3**).

The temperature curve of CC is characterized by aeration happenings, which can be identified as abrupt temperature drops (when the sensor was removed from the pile) and peaks (after oxygen supply) in the curve and is shown in **Figure 3**. The maximum temperature of 73 °C was achieved three days after setting up on 9th of June.

Fungi *(Basidiomycota)* were observed on the surfaces of MC1 & 2, starting on the 24th of June (see **Figure A 2**). The short-lived fruit bodies seemed to dry out fast and died already two days later. After some rainy days in the beginning of July, water had collected on the concrete plate and the heaps were soaked about 10 cm from the ground. On 5th of July, fungi were found inside all EM measurement collars of MC2. Three days later, fungi were still abundant on all MC heaps. On 12th of July, fungi were mostly only visible on the moist zones at the bottom and in the areas shaded by the surrounding strawbales. In general, on MC2 & 3 more fungi were observed than on MC1. Fungi could be observed for the first time on CC on 16th of July. The beginning of August was hot and dry, but in the second half of the month the weather was getting cooler and wetter. On 23rd of August, just before applying the heaps to the field, dried fungi and even single weeds could still be observed on MC1 & 2.

3.1.2 Compost substrate properties

Compositional changes of the substrates during the composting period could be observed in all analysed treatments (MC1 & 2, CC) and are presented in **Table 2**. Change-ratios (∂) can be found on the right side of the table and biggest changes are marked bold. The results of CC need to be interpreted with care, because the values before composting are only a calculated mean of the MC1 & 2 start-substrate-values (since the CC start-substrate was not analysed separately). Supplementary analysis results of MC3 after composting can be found in **Table A 13**.

Ash contents in CC raised about 22 – 28 % during decomposition, while in MC1 the change was negligible and in MC2 it raised about 12 –13 %. A higher decrease of C_{tot} in CC could be observed, compared to MC1 & 2. Consequently, MC1 & 2 were found to have 27 % and 36 % higher C_{tot} than CC, respectively. A similar picture emerged with N-content: MC1 & 2 showed

9- and 13-times higher NH_4-N values than CC, respectively. P contents, however, follow an opposite pattern: MC1 & 2 showed 30 % and 35 % lower values, respectively, compared to CC.

Van Soest analysis revealed substantial differences between treatments in C-fractions (Table 2). Higher contents of lignin (+35 %) and insoluble fibres (+17 %) could be found in CC, compared to MC1 & 2. To exclude biases due to different ash contents, the C-fractions of the Van Soest analysis were presented as ash-free DM.

Table 2*: Compost substrate properties and carbon (C) fractions, according to Van Soest, of MC1 & 2 and CC before (05.06.20) and after (22.09.20) composting and the rate of change (∂) after composting. CC values for 05.06. are calculated values as average from MC1 & 2). Biggest change in each category is indicated in bold numbers. Supplementary analysis results of MC3 after composting can be found in* ***Table A 13****.*

	Before composting (05.06.20)			**After composting** (22.09.20)			**Change during composting** (∂ 05.06. – 22.09.)		
	MC1	**MC2**	**CC***	**MC1**	**MC2**	**CC**	**MC1**	**MC2**	**CC**
DM [%]	50 / 54^{b}	43 / 47^{b}	47 / 50^{b}	53 / 61^{b}	40 / 59^{b}	58 / 58^{b}	3 / 7^{b}	7 / **11**^{b}	**12** / 7^{b}
Ash [% FM]	19	18	19	15	31	41	-4	13	**22**
Ash [% DM] ^{c}	45	29	37	49	41	65	3	12	**28**
pH	8.5	6.8	7.7	7.9	9.0	8.6	-0.6	**2.1**	0.9
P/N	0.2	0.4	0.3	0.1	0.1	0.3	-0.1	**-0.7**	0.2
C/N	16 / 20^{a}	14 / 22^{a}	15 / 21^{a}	14 / 21^{a}	9 / 21^{a}	11 / 14^{a}	-2 / 2^{a}	**-5 /** -1^{a}	-4 / **-7**^{a}
C$_{\text{-tot}}$ [% DM] ^{a}	27	33	30	28	30	22	1	-2	**-8**
N$_{\text{-tot}}$ [kg Mg^{-1} DM]	10 / 14^{a}	9 / 15^{a}	9 / 14^{a}	14 / 13^{a}	11 / 15^{a}	8 / 16^{a}	**4** / -1^{a}	3 / -1^{a}	-1 / **2**^{a}
NH$_4$-N [kg Mg^{-1} DM]	4.0	2.5	3.3	6.4	4.5	0.5	2.4	2.0	**-2.8**
P [kg Mg^{-1} DM]	1.8	3.3	2.6	1.5	1.6	2.3	-0.3	**-1.7**	-0.3
K [kg Mg^{-1} DM]	8.1	6.5	7.3	2.9	4.0	4.0	**-5.2**	-2.5	-3.3
Mg [kg Mg^{-1} DM]	1.5	2.8	2.2	1.1	1.1	1.8	-0.4	**-1.7**	-0.4
Na [kg Mg^{-1} DM]	1.0	0.7	0.9	0.4	0.6	0.6	**-0.6**	-0.2	-0.3
S [kg Mg^{-1} DM]	1.8	1.3	1.6	0.9	1.0	1.2	**-0.9**	-0.3	-0.4
Van Soest analysis of C- fractions (% of ash-free DM)									
Fibres insoluble^{c} [%]	76.9	69.7	72.8	66.6	64.4	78.4	**-10.3**	-5.3	5.6
Fibres soluble^{c} [%]	5.5	4.9	5.2	6.8	6.3	7.5	1.3	1.3	**2.3**
Soluble non-fibres^{c} [%]	20.1	30.4	25.9	28.3	24.0	22.1	**8.2**	-6.4	-3.8
Soluble components^{c} [%]	25.6	35.4	31.1	35.1	30.3	29.6	**9.5**	-5.1	-1.5
Hemicellulose^{c} [%]	23.9	15.4	19.1	15.4	14.0	15.9	**-8.5**	-1.4	-3.3
Cellulose^{c} [%]	33.1	34.5	33.9	30.1	36.5	25.0	-2.9	2.0	**-8.8**
Lignin^{c} [%]	17.4	14.7	15.9	19.4	19.2	29.5	1.9	4.5	**13.5**

^{a} Results from CU, ^{b} Results from SLU, ^{c} results from Artemis, other results are from Eurofins. * Calculated average of MC1 & 2. FM: fresh matter, DM: dry matter.

3.1.3 Machinery demand

Records of machinery hours, spent on composting, show that on average 10 minutes were spent per m^3 of start-substrate. Whereas MC treatments demanded each 6 minutes and CC about 41 minutes per m^3 of start-substrate (Table 3). In other words, processing 1 m^3 of CC demanded about 7 times more work than 1 m^3 of MC. A more sophisticated view on the work-economics, excluding the transport of materials, reveals, that setting up of one MC-heap was done with an efficiency of 24 m^3 h^{-1} with no further machinery input needed. In contrast, setting up and especially the maintenance (mechanical aerating) of CC caused a higher machinery demand, which resulted in a lower efficiency of only 1.6 m^3 h^{-1}.

***Table 3**: Machinery input [h m^3] for MC1 & 2 and CC and efficiency of machinery use [m^3 h^{-1}].*

Date	Task	All treatments	MC1	MC2	CC
05.06.20	Transport of substrates [h]	3.00	1.37	1.24	0.39
05.06.20	Setting up composts [h]	2.00	0.99	0.91	0.10
07.06.- 23.08.20	Aerating CC (17 times) [h]	4.25	-	-	4.25
Total hours [h]		**9.3**	**2.4**	**2.2**	**4.7**
Hours spent per cubic meter [h m^{-3}]		**0.2**	**0.1**	**0.1**	**0.7**
Efficiency of specific machinery demand [m^3 h^{-1}] *		**8.5**	**24.0**	**24.0**	**1.6**

* Only setting up of composts and maintenance (aerating CC) are included (excl. transport).

To evaluate the machinery labour efficiency per kg N of MC and CC, the machinery labour input shown in Table 3 has been combined with numbers from the substrate analyses (Table 2). The result, shown in Table 4, illustrates the 35 % lower N-density of the CC end-substrate, compared to MC, according to the numbers retrieved from Eurofins. From the lower N-density, on the one hand, and the higher labour demand on the other, it results that the machinery input per kg N in CC was 0.12 hours, while in MC it was only one tenth of that (0.01 h kg^{-1} N). Additional literature data from Zemánek (2002) was used for comparison and shows, that in theory very high efficiencies could be achieved by CC, when using a windrow turner instead of a wheel loader for aeration.

***Table 4**: Nitrogen (N) densities and machinery input [h kg-1 N] for MC1 & 2 and CC.*

	MC1	MC2	MC ø	CC	CC* with windrow turner
Required compost quantity [kg] for 1 kg N **	74	91	83	128	128
Machinery input [h kg^{-1} N]	0.01	0.01	0.01	0.12	0.001-0.005 *

* Hypothetical calculations, based on Zemánek (2002)
** Depending on N_{tot} (**Table 2**, Eurofins)

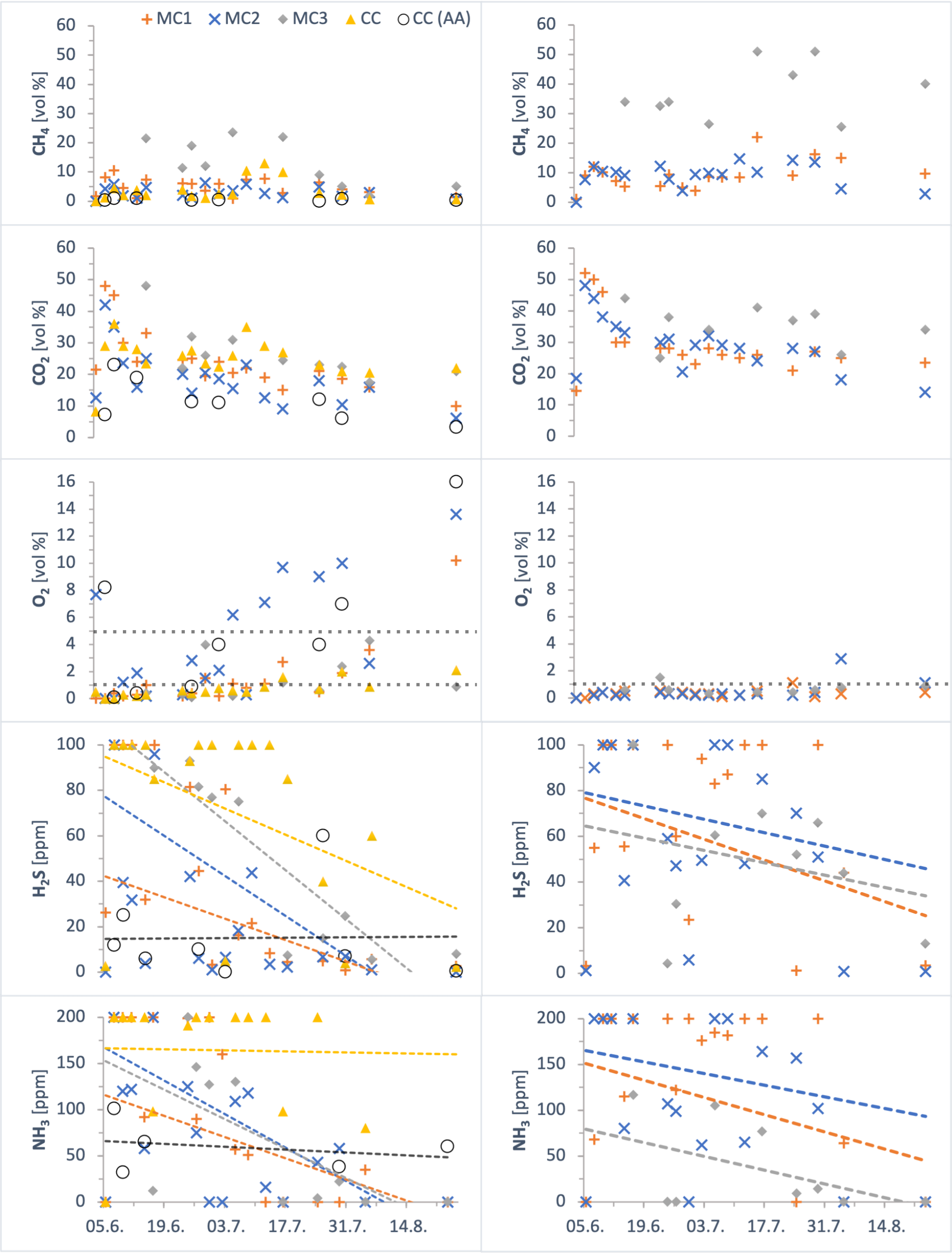
3.1.4 Pore gas concentrations in compost heaps

The developments of the PG inside the compost heaps are visualised in **Figure 2** and the mean PGC of the composting period are summarized in **Table 5**.

Regarding O_2, major differences could be observed between the MC treatments. While MC1 & 3 stayed most of the measurement period below the threshold of 1 vol% for MC composting, MC2 showed O_2 contents above 1 vol% in 0.65 m depth almost throughout the entire period. **Table 5** and **Figure 2** indicate that CC showed O_2 values below 5 vol% (which is the threshold for CC) before aeration events especially in the thermophilic phase (until the end of June). Only in less than half of the measurement occasions after physical aeration (AA), 5 vol% have been exceeded.

In average, aeration happenings raised O_2 levels about 4 vol%. Looking at CO_2 and CH_4 values in CC shows, that these gases have been decreased after aeration happenings (CO_2: -14 vol%, CH_4: -3 vol%, see **Table 5** and **Figure 2**). Similar applies to H_2S (-56 ppm) and NH_3 (-105 ppm).

On average, CH_4 concentrations of CC were, with around 4 vol%, close to the values of MC1 & 2 (**Figure 2**). Similar applies to CO_2: with 25 vol% on average CC showed no clear difference to the MC treatments. MC3 showed the highest mean value (0.65 m: 27 vol%) followed by MC1 (0.65 m: 24 vol%) and MC2 (0.65 m: 19 vol %), see **Table 5**.



Pore gas measurements in 0.65 m depth below surface. **Pore gas measurements in 1.50 m depth below surface.**

Figure 2: *Pore gases (PG) of MC1-3 and CC measured in 0.65 m (left column) and 1.5 m (right column) depth below surface, within the measurement period 5th of June to 23rd of August. CC (AA) stands for measurements, performed after aeration happenings. Concentrations are in the units vol% for CH_4, CO_2, O_2 and ppm for H_2S and NH_3. Note the different scales, which have been chosen for better resolution, and that the maximum measurement range for H_2S and NH_3 was 100 ppm, and 200 ppm, respectively. The dotted lines in the O_2 graphs indicate the max. oxygen threshold for MC (Witte n. d.-a) and min. for CC (Rynk et al. 1992). The dotted lines in H_2S and NH_3 graphs indicate linear trends of the colour-matching treatments.*

Table 5: *Temperature, moisture, pore gas concentrations (PGC) (mean: ø) and emission (EM) sums (∑) of MC1-3 and CC during the composting period of 79 days (05.06. – 23.09.). PGC are presented separately for both measurement depths in MC (0.65 m and 1.5 m) and an average value between both is given. CC PGC values include measurements before aeration (BA) and after aeration (AA) and the average change (∂ BA – AA). Ranges (min.-max. values) of PGC measurements or standard errors (SE) for EM measurements are given in brackets.*

		MC1		MC2		MC3			CC	
	Measurement depth	**Ø**	**Range**	**Ø**	**Range**	**Ø**	**Range**	**Measurement timing**	**Ø**	**Range**
Temperature [°C]		53	(44-55)	58	(49-61)	50	(38-55)		46	(max. 73)
Moisture [% H_2O]		44	(41-47)	55	(30-60)	-	-		-	-
Pore gas concentration										
CH_4 PGC [vol%]	0.65 m	5	(1-11)	3	(0-6)	13	(2-24)	BA	4	(0-13)
	1.50 m	9	(1-22)	9	(0-15)	38	(26-51)	AA	1	(0-1)
	Ø 0.65 – 1.50 m	**7**		**6**		**26**		∂ (BA – AA)	-3	- (0-1)
CO_2 PGC [vol%]	0.65 m	24	(10-48)	19	(6-42)	27	(18-48)	BA	25	(8-36)
	1.50 m	29	(15-52)	29	(14-48)	35	(25-44)	AA	12	(3-23)
	Ø 0.65 – 1.50 m	**27**		**34**		**31**		∂ (BA – AA)	-13	- (9-22)
O_2 PGC [vol%]	0.65 m	1	(0-10)	4	(0-14)	1	(0-4)	BA	1	(0-2)
	1.50 m	0	(0-1)	0	(0-3)	1	(0-2)	AA	5	(0-16)
	Ø 0.65 – 1.50 m	**1**		**2**		**1**		∂ (BA – AA)	4	(0-16)
H_2S PGC [ppm]	0.65 m	24	(1-100)	18	(0-100)	48	(6-93)	BA	42	(2-93)
	1.50 m	46	(1-100)	42	(0-100)	43	(4-100)	AA	15	(0 - 60)
	Ø 0.65 – 1.50 m	**35**		**30**		**46**		∂ (BA – AA)	-27	- (0-94)
NH_3 PGC [ppm]	0.65 m	53	(0-200)	53	(0-200)	49	(0-200)	BA	93	(0-191)
	1.50 m	91	(0-200)	70	(0-200)	36	(0-117)	AA	59	(32-101)
	Ø 0.65 – 1.50 m	**72**		**62**		**56**		∂ (BA – AA)	-34	- (99-178)
Emissions		**∑**	**SE**	**∑**	**SE**	**∑**	**SE**		**∑**	**SE**
N_2O-N EM [g Mg^{-1}]		13	(2)	11	(2)	-			34	(4)
CH_4-C EM [g Mg^{-1}]		793	(230)	962	(214)	-			555	(174)
CO_2-C EM [g Mg^{-1}]		7 020	(300)	8 119	(614)	-			18 582	(982)

Abbreviations: BA = before aeration; AA = after aeration; SE = Standard error. MC1 & 2, CC (BA): N = 18; CC (AA): N = 7; MC3: N=10.

3.1.5 Emissions from composting

The development of EM (N_2O, CH_4 and CO_2) measured above MC1, MC2 and CC heaps, during the measurement period 05.06. – 23.08.2020 are visualized in **Figure 3**. EM sums can be found in **Table 5**. Note, that composting related EM are expressed in relation to the underlying mass of substrate (g Mg^{-1}).

3.1.5.1 Nitrous oxide (N_2O) emissions from composting

N_2O EM started off at a rather low level in all treatments (< 0.0 g Mg^{-1} d^{-1}, see **Figure 3**). After one month of composting, in the beginning of June, EM began to rise and especially in CC high peaks (up to 1.66 g Mg^{-1} d^{-1}) occurred until the end of July. EM showed a downward trend in all treatments during August. The high EM period in July, which is accompanied by big standard errors in CC (**Figure 3**), contributed a lot to the result that the N_2O EM sum of CC (34 g Mg^{-1} d^{-1}) is almost three times higher than in MC1 (13 g Mg^{-1} d^{-1}) and more than three times higher than MC2 (11 g Mg^{-1} d^{-1}, see **Table 5**).

3.1.5.2 Methane (CH_4) emissions from composting

CC and MC1 EM started off with medium values (< 13 g Mg^{-1} d^{-1}) and a rather similar curve shape, while MC2 showed higher EM (up to 18 g Mg^{-1} d^{-1}) already from the second measurement occasion on (**Figure 3**). Comparable to the development of the N_2O EM, July was characterized by higher EM in all treatments, accompanied with great standard errors. From the 20th of July on, CC showed very low values only (< 5 g Mg^{-1} d^{-1}), while the MC treatments remained on a higher range (0.5 – 17.0 g Mg^{-1} d^{-1}). The described patterns resulted in MC2 showing the biggest EM sum (962 g Mg^{-1} d^{-1}), followed by MC1 (793 g Mg^{-1} d^{-1}) and CC (555 g Mg^{-1} d^{-1}, see **Table 5**).

3.1.5.3 Carbon dioxide (CO_2) emissions from composting

CO_2 EM started off with a high peak in CC (906 g Mg^{-1} d d^{-1}). After that a falling trend followed, with some peaks in between, until the end for all treatments. Consistently, MC treatments showed lower CO_2 EM than CC, with similar EM heights and curves. This resulted in CC having over twice as much CO_2 EM (18582 g Mg^{-1} d^{-1}) as MC2 (8119 g Mg^{-1} d d^{-1}) or MC1 (7020 g Mg^{-1} d^{-1}, see **Table 5**).

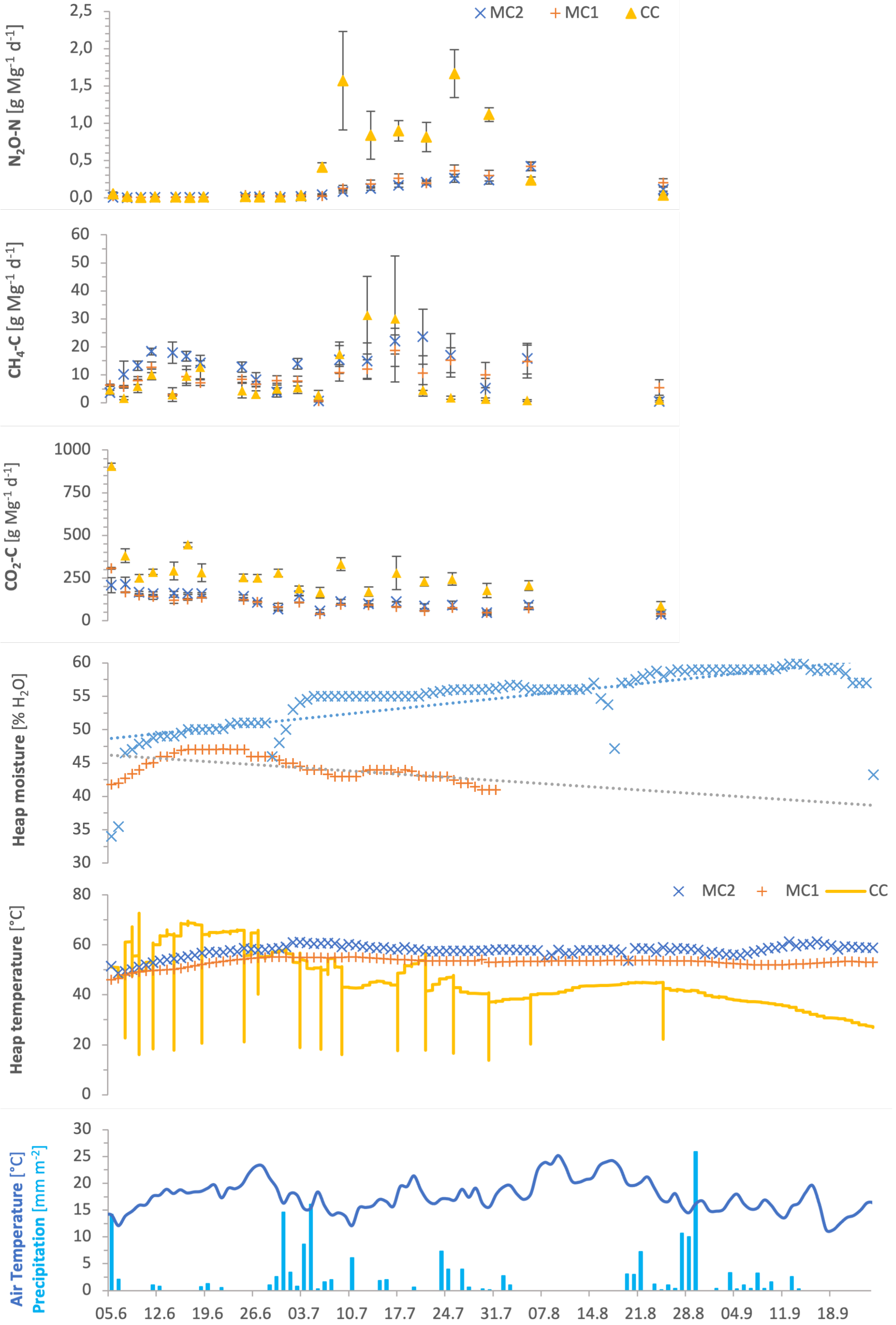


Figure 3*: N_2O, CH_4 and CO_2 composting emissions (EM) of MC1 & 2 and CC. Note the different scales for improved visibility. Last EM-measurement was 23rd of August. Error bars show the standard error (SE) between single measurement chambers for each measurement. Additionally, heap moisture, with trendlines indicated in grey, and heap temperatures are displayed. Punctual drops in MC2 moisture result from short withdrawal of the sensor for technical control purposes. Weather data was retrieved from the nearby weather station (SMHI 2021).*

3.2 Part two: Field application

3.2.1 Environmental conditions and soil properties

The mean air temperature during the 78-day long period of field measurements was 11 °C and precipitation sum was 158 mm. Starting with around 16 °C on 23rd of September, temperatures deceased until 5 °C on 19th of October (**Figure 4**). Higher varying temperatures followed until the first days of November, before temperatures decreased again. On 28th of November temperature dropped to the freezing point. Afterwards temperature never increased more than 7 °C until the end of measurements on 10th of December.

Precipitation started off with an irregular heavy rain (38 mm) two days after the start of measurements, which directly resulted in an increase in soil moisture (+17 % H_2O, see **Figure 4**). After that, precipitation was more evenly distributed and soil moisture levelled at around 40 % H_2O, until the end of October, when more precipitation increased soil moisture further to around 60 %. In the end of the measurement period soil moisture was around 70 %.

Soil temperature started off with 16 °C and decreased constantly to 5 °C, when records unfortunately stopped due to technical issues on 28th of November (**Figure 4**). The Albrecht soil analysis showed the chemical soil status before compost application, which can be reviewed in appendix for further information (**Figure A 1**).

3.2.2 Emissions from field application of composts

The developments of EM, released from with compost treated soil during the measurement period 23.09. – 10.12.2020, are displayed in **Figure 4** and the EM sums in **Table 6**. Note, that soil EM are expressed in relation to the fields surface (g ha^{-1}), compared to the composting related EM, which were expressed per megagram of compost (g Mg^{-1}).

***Table 6**: N_2O, CH_4 and CO_2 field emission (EM) fluxes [g ha^{-1}] after the application of MC1-3 and CC over a period of 78 days (23.09. – 10.12.). Standard errors (SE) are given in brackets.*

	MC1	**MC2**	**MC3**	**CC**
N_2O-N [g ha^{-1}]	2 609 (659)	1 992 (321)	853 (361)	549 (152)
CH_4-C [g ha^{-1}]	35 (137)	23 (65)	-54 (63)	277 (46)
CO_2-C [g ha^{-1}]	1 864 915 (141 058)	2 141 923 (244 704)	1 537 544 (183 150)	1 626 558 (64 042)

3.2.2.1 Nitrous oxide (N_2O) emissions from the field

N_2O EM started off with low values (< 4 g ha^{-1} d^{-1}) in all treatments (**Table 6**). One day after a heavy precipitation event (38 L m^2) the second measurement, on 26th of September, captured an extraordinarily high peak in all treatments with a maximum of 581 g ha^{-1} d^{-1} in MC1 (**Figure 4**). Already on the next measurement occasion, on 30th of September, EM in all treatments have decreased again (12 – 30 g ha^{-1} d-^{1}) and from then on constantly continued to decrease below 1 g ha^{-1} d^{-1} at the last measurement day on 10th of December. The huge peaks on 26th of September, especially in the MC treatments, contributed much to the resulting total EM of MC1, showing the biggest EM sum (2609 g ha^{-1}), followed by MC2 (1992 g ha^{-1}), MC3 (853 g ha^{-1}) and CC (549 g ha^{-1}).

3.2.2.2 Methane (CH_4) emissions from the field

CH_4 EM showed an interesting pattern: the beginning of the measurement period was characterized by much variation between all treatments with positive and negative values (**Figure 4**). From the beginning of October on, CC showed a rising trend until the end, what resulted in the highest EM sum of 277 g ha^{-1} d^{-1}. Interestingly, measurements on MC treatments often showed negative CH_4 values, but MC1 & 2 raised again in the end of the period. In total, MC2 & 3 showed low CH_4 EM sums (23 and 35 g ha^{-1} d^{-1}), which were in the range of only one tenth of the EM of CC. Only MC3 showed predominantly negative values throughout the measurement period, what resulted in a negative balance (-54 g ha^{-1} d^{-1}, see **Table 6**).

3.2.2.3 Carbon dioxide (CO_2) emissions from the field

CO_2 EM were to be found on high levels in all treatments (**Table 6**). Starting off at moderate levels (12 000 – 22 000 g ha^{-1} d^{-1}), all treatments increased, with the highest peak in MC1: 42 312 g ha^{-1} d^{-1} on 26th of September, analogous to N_2O EM pattern (**Figure 4**). MC1 & 2 were located on higher levels, while MC3 and CC were showing similar curve developments, but on a lower level. After a second peak on 25th of October in CC and MC2 (32 540 and 37 404 g ha^{-1} d^{-1}), which occurred during a phase of rain, EM decreased in all treatments to a level between 10 849 – 17 015 g ha^{-1} d^{-1}, on the last measurement. This resulted in the following EM sums in descending order: MC2: 2 141 923 g ha^{-1} d^{-1}, MC1: 1 864 915 g ha^{-1} d^{-1}, CC: 1 626 558 g ha^{-1} d^{-1}, MC3: 1 537 544 g ha^{-1} d^{-1}.

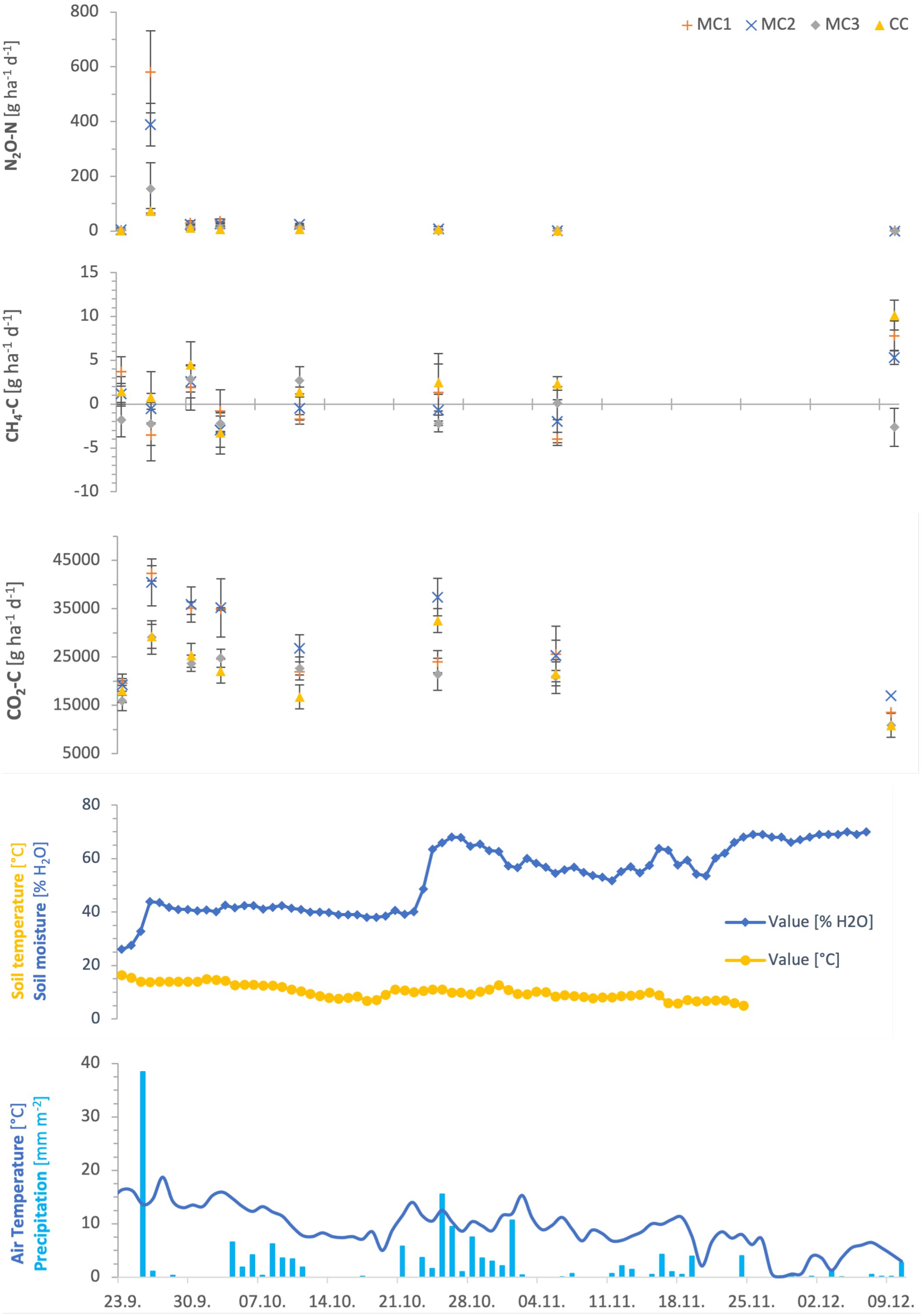


***Figure 4**: N_2O, CH_4 and CO_2 field emissions (EM) of MC1-3 and CC.Note the different scales for improved visibility and the differing unit (g ha^{-1}), compared to the composting related EM (g Mg^{-1}). Error bars show the standard error (SE) between single EM measurement chambers for each measurement. Soil temperature and moisture data was measured constantly and is shown below the EM graphs. Weather data was retrieved from the nearby weather station (SMHI 2021).*

3.3 Part three: Climate impact of composting and field emissions

The GHG EM measured in the composting treatments (MC1 & 2 and CC) and the field treatments (MC1-3 and CC) were transformed into $CO_{2\text{-eq}}$ on the basis of GWP_{100} (see 4.6) to compare their total climate impact (**Figure 5**).

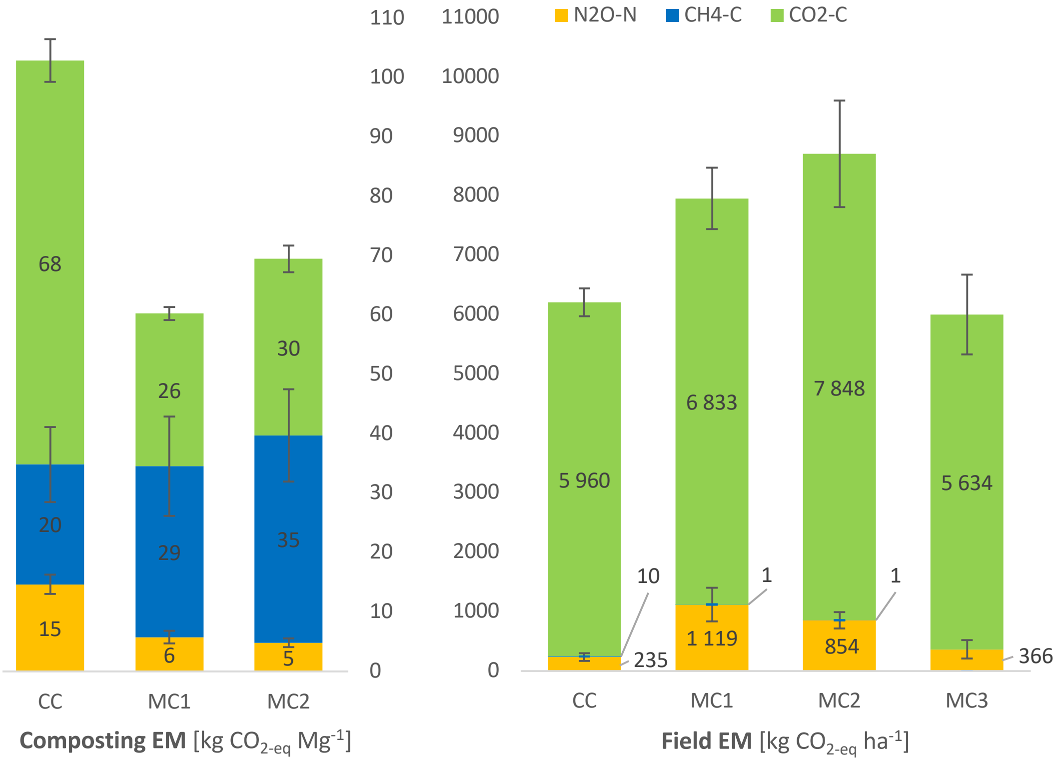


***Figure 5**: Climate impact of emissions (EM) from composting and field application [$CO_{2\text{-eq}}$]. Composting EM of MC1 & 2 and CC on the left side of the figure in kg $CO_{2\text{-eq}}$ Mg^{-1} and field EM of MC1-3 and CC on the right side in kg $CO_{2\text{-eq}}$ ha^{-1} – note the different scales and units! Error bars show the standard error (SE) between the repetitions of the EM measurement chambers for each measurement.*

Figure 5 shows that during composting MC1 & 2 have a 40 % and 30 % lower climate impact than CC, respectively. In CC CO_2 EM had the largest contribution of about 66 %, whereas in both MC treatments CO_2 accounted for 43 %. If CO_2 would have not been accounted for, EM sums of all treatments would appear very similar in size, with CC equal to MC1 (**Figure 5**). In both MC treatments, CH_4 accounted for a large share (48 – 50 %) of the climate impact, whereas in CC it only accounted for 20 %. The contribution of N_2O was rather low in all treatments, but twice as high in CC (14 %) than in MC2 (7 %).

Looking at the field EM shows that MC1 & 2 have a 28 % and 40 % higher climate impact than CC, respectively (**Figure 5**). MC3, on the other hand, was in the same range of magnitude as CC, with a 3 % lower climate impact. CO_2 had by far the largest share in all treatments (86 – 96 %) during field application. The next biggest share was N_2O with only 4 – 14 %, while the CH_4 EM were negligibly small in all treatments (< 1 %). If CO_2 would be excluded from the climate impact of the field EM, the bigger picture would remain similar, with MC1 & 2 having the largest climate impacts, but the distance to MC3 and CC would increase, with CC having the smallest impact.

To enable the comparability of composting and field EM, the mass of compost applied to the field (10 Mg ha^{-1}) must be considered. This means that ten times the composting EM, shown in **Figure 5**, relate to one hectare of the field (see **Table 7**). Comparing the climate impact (in $CO_{2\text{-eq}}$) of composting and field EM sums shows that the field EM had a much larger impact (about 90 % of the total GHG EM, see **Table 7**), while resulting from periods of similar lengths (see 4.7). In this consideration, it must be taken into account that background EM from the soil itself can make a substantial contribution to the measured EM in the field, which cannot be factored out here (for further discussion see 4.7.3). Therefore, it is not appropriate to simply add up the EM sums. If one were to do this, one might conclude that CC had the lowest total GHG EM, followed by MC1 (+18 %) and MC2 (+30 %). Therefore, **Table 7** provides another way of looking at it: if the EM were expressed per kilogram of N applied to the field a different picture would emerge. As CC had lower N_{tot} contents (see **Table 2**) MC1 showed 32 % (-26 $CO_{2\text{-eq}}$ ha^{-1}) lower total GHG EM and MC2 5 % (-5 $CO_{2\text{-eq}}$ ha^{-1}) lower total GHG EM per kg N than CC.

Table *7: Composting and field emissions (EM) of MC1 & 2 and CC [kg $CO_{2\text{-eq}}$ ha^{-1}] in relation to the field area [ha] and the N applied with the compost [kg N]. Differences of MC1 & 2 to CC are indicated in the columns to the right side and biggest differences are marked in bold.*

		CC	**MC1**	**MC2**	**Difference MC1 to CC**	**Difference MC2 to CC**
Composting EM	N_2O	150	60	50	-90	**-100**
[kg $CO_{2\text{-eq}}$ ha^{-1}]	CH_4	200	290	350	90	**150**
	CO_2	680	260	300	**-420**	-380
	All GHG	1030	610	700	**-420**	-330
Field EM [kg $CO_{2\text{-eq}}$ ha^{-1}]	N_2O	235	1119	854	**884**	619
	CH_4	10	1	1	-9	-9
	CO_2	5960	6833	7848	873	**1888**
	All GHG	6205	7953	8703	1748	**2498**
Composting & field EM	N_2O	385	1179	904	**794**	519
[kg $CO_{2\text{-eq}}$ ha^{-1}]	CH_4	210	291	351	81	**141**
	CO_2	6640	7093	8148	453	**1508**
	Total GHG	7235	8563	9403	1328	**2168**
N applied with compost [kg N ha^{-1}]		80	140	110	**60**	30
Total GHG per kg N [kg $CO_{2\text{-eq}}$ kg^{-1} N]		90	61	85	**-29**	-5

3.4 Part four: Farmers interviews

In the following section the results of the interviews with seven farmers in Germany and Austria are presented. The farm site's key data ranged from 2 – 560 m above sea level with 400 – 1000 mm of precipitation and 7.8 – 10 °C annual mean temperature. In the following analysis numbers in brackets behind the statements show how many farmers have made the statement. Most farms worked according to organic (2), biodynamic (1) and or regenerative (4) principles, equipped with areas from 10 – 120 ha. Moreover, the diversity of the participating farms was characterized by different operating branches, like arable farming (6), arboriculture (1), forestry (1) and livestock, like cattle (4), chicken (2) or swine (1). In the following, only statements made by more than one farmer will be mentioned.

3.4.1 Farmers motivations for on-farm composting

General motivations, mentioned by the farmers to work with on-farm composting, were first and foremost to avoid losses from manure handling (3) and secondly to enhance soil life (3). Moreover, considerations to utilize locally available resources and close nutrient cycles also seem to be important (2). Most farmers have had no experience with on-farm composting before they started MC composting (5) while others have more than 20 years of experience with CC on their farms (2). Most farmers have started with MC between 2016 and 2019 (5) and only two of them have started already 10 years ago. They became aware of the method and learned about it during seminars with Walter Witte (5), from other farmers (2), in soil masterclasses (2) or agricultural schools (1).

3.4.2 Farmers motivations for MC composting

Farmers were working with MC mainly since it is perceived as an inexpensive method (4), furthermore, to reduce losses (3) (especially C-losses (2)) and enhance soil fertility (3). With the aim of minimizing losses, odour pollution can be reduced (2) as well. Some farmers just liked to try something new (2) and most of them mentioned the comparable low work and machinery demand throughout the interviews as advantage of MC.

3.4.3 Factors for a successful MC process and difficulties

The following was highlighted as important for successfully working with MC:

1. lignin components (WC) (3)
2. starting simple and small scale to get experience (3)
3. material composition in general (2)

4. surface constitution and preparation (2)
5. machinery (2)
6. sufficient mixing of the substrates (2)

Difficulties were mentioned in standardising the method (3), e. g. by developing recipes and their reproducibility. Therefore, knowledge about parameters for process control and better instructions were requested (2). Mentioned areas for future research related to the impact of composts and MC on soil life, with focus on the biology and microbial community composition, by more than 50 % of the farmers (4). Moreover, the compatibility of MC substrates with regional fertilization regulations seemed to be unclear and should be clarified (2).

3.4.4 Used substrate compositions

All (7) farms were composting manures (cattle (5), horse (3), chicken (3), pig (1), sheep (1)) together with WC. Some of them added stone flour (2), grass cuttings (1), old seeds (1) or reed (1). Most farmers made vague statements about their recipes and all of them stated varying substrate compositions, depending on substrate availability or target crop (and fertilization value). If stated, substrate compositions ranged from 25 – 70 % manure and 30 – 70 % WC.

3.4.5 Procedures of constructing MC heaps

A generalised procedure of setting up MC heaps can be summarised as follows:

1. Collection of the substrates (preferably during a short period)
2. Mixing with a wheel loader
3. (Maceration)
4. Setting up the heap with either a manure spreader or mixing it with a compost turner and compacting the surface

The duration of decomposition ranged from 1 – 24 months and was around 3 – 6 months (3) for most of the farms. The favourable time for setting up MC heaps seemed to be when substrates are available (6). Two farmers favour frozen ground, to avoid compaction of machinery and two favour summer before winter. Machinery equipment was mostly the wheel loader (7) and the manure spreader (6). Two farmers were using tractor driven compost turners. Most farmers were processing the substrates on unpaved ground (5) (e. g. field borders), three farmers used available concrete plates or paved grounds with walls (e. g. bunker silos). The heap was usually formed like a big trapezoid windrow (7) (1.0 – 2.5 m high, 3 – 5 m wide, 20 – 25 m long, depending on substrate amount). Most farmers compacted the surface of each heap with the wheel loader's shovel (6).

3.4.6 Parameters for process control and reference values

The most frequently measured parameters for process control were temperature (7) and moisture (2). (The latter is mostly a sensory measure only, by pressing the substrate in one hand and observing water excretion.) Visual observations seem to be an important control measure moreover (3). Statements about optimal heap temperatures ranged between 35 – 60 °C, most statements were between 40 – 60 °C (5). Since moisture is mostly measured by sensory feeling, absolute values for an optimal range were scarce, but three statements were in the range between 40 – 60 % water content.

3.4.7 Field application of MC substrates

Farmers applied the MC end-substrate with 5 – 30 Mg ha^{-1} a^{-1} either in spring (5) or autumn (4) into green crop stands and growing cover crops (4) or before sowing (5). Two stated to apply it on grain or maize stubble also. The most common effect of applying MC was that crops improved visually (3).

4 Discussion

The main findings, that can serve as a starting point for answering the research questions posed, are the following and will be discussed in subchapters throughout this chapter.

CC and MC treatments showed major differences in machinery demand: MC provided 1 kg N with about one tenth of the machinery input compared to CC (see 3.1.3). Therefore, the first hypothesis – that, *under farm conditions and with existing farm machinery, MC provides 1 kg of N with less machinery labour than CC* – can be supported. This result correlated very well with findings from the farmers' interviews, which revealed that the main reason, to use MC on their farms was, that it is perceived as an inexpensive method (see 3.4.2). Other reasons were that farmers believe that MC can help to utilize locally available resources, reduce nutrient losses on the farm while having positive effects on soil fertility. Similar reasons were stated as motivation for on-farm composting in general (see 3.4.1).

Substrate analyses revealed 27 – 36 % higher C_{tot} contents of MC end-substrates, compared to CC (see 3.1.2). Therefore, at least the first part of the third hypothesis – that *MC end-substrates contain more total C* – can be supported, which is in line with the perceptions of the interviewed farmers. Due to lower shares of insoluble C fractions in MC end-substrates (lignin -35 %, insoluble fibres -17 %, see 3.1.2) the second half of this hypothesis – that *MC end-substrates contain larger fractions of insoluble C than CC end-substrates* – needs to be rejected.

MC showed 30 – 40 % lower total GHG EM (calculated as $CO_{2\text{-eq}}$, based on GWP_{100}) during the composting phase compared to CC (see 3.3). However, during the first 11 weeks after field application MC1 & 2 showed 28 % and 40 % higher GHG EM than CC, respectively. The picture is less clear when MC3 – which had a different substrate composition and on which EM only were measured during field application – is included: with 3 % lower EM than CC, MC3 was very similar to it. An attempt to make a statement regarding the second hypothesis – that *MC releases less GHG (N_2O, CH_4, CO_2) than CC during the composting process and during the first 11 weeks after field application* – can therefore only be made through two partial statements:

1. MC1 & 2 released less GHG during the composting process, compared to CC. Therefore, the first part of this hypothesis can be supported.
2. During the first 11 weeks after field application MC1 & 2 released more GHG, compared to CC. Hence, based on the results of these treatments, where measurements both during composting and in the field were available, the second part of the hypothesis needs to be rejected.

The present study found furthermore that, even though farmers implement the MC method differently in detail on their farms (see 3.4.4 and 3.4.6), most of them point out similar difficulties (see 3.4.3). These were mostly to standardise the method and a knowledge gap in parameters for process control. In addition, many farmers asked for insights into the effects of CC and MC on soil life, focusing on the composition of the microbial community. Moreover, the compatibility of MC substrates with regional fertilization regulations seemed to be unclear and should be clarified.

4.1 Process analytics and evaluation of the compliance of the composting processes with the CC and MC methods

If a composting process is to be evaluated, it is important to determine whether the practical implementation in the trial also corresponded to the theory. In order to assess the compliance of the MC and CC treatments with their respective methods, visual observations, temperature, moisture and PGC progressions within the heaps are considered in this chapter. Like Boldrin et al. (2009) concludes, management and type of technology is crucial for the generation (or suppression) of GHG EM and the decomposition of OM for CC – the same is expected to apply for MC (Witte n. d.-a).

For all treatments applies, that rainwater which stood on the concrete plate during several occasions and thus moistened the bottom of the heaps (see 3.1.1), was probably not conducive to a proper composting process. This is because wet zones with resulting anaerobic conditions are not desirable in either MC or in CC (see 4.3.2).

4.1.1 CC treatment

CC showed the typical temperature curve for aerobic windrow composting (**Figure 3**) – including thermophilic, mesophilic and maturation phases – which is described in literature (Peigné & Girardin 2004; Wagner & Illmer 2004). With a temperature peak of 73 °C and average temperatures between 45 – 65 °C over several weeks, hygienisation of CC should be ensured (Wagner & Illmer 2004). After the last aeration on 23rd of August temperatures did not increase anymore and constantly fell, which indicated the successful entry into the maturation phase (Maheshwari 2014). The pH value increased from 7.7 to 8.6 during decomposition, which is in line with literature values (Linzner *et al.* 2005).

Regarding O_2 PGC, which is considered a key parameter in process control, CC showed very low values during the entire composting phase (**Figure 2**), compared to suggestions from literature (Rynk *et al.* 1992; Wagner & Illmer 2004; Puyuelo *et al.* 2010). Only by half of the aeration happenings O_2 PGC was raised above the recommended threshold (**Figure 2**). Hubbe (2014) confirms that these partially O_2-limited conditions are often observed in composts labelled as aerobic treatment. This is a cause for concern in terms of EM generation (Amlinger *et al.* 2008; Saer *et al.* 2013) and will be elaborated on in 4.3. In addition, high PGC in CC, such as CO_2, CH_4, H_2S and NH_3, indicate a non-typical decomposition process and their reduction during aeration events (**Table 5** and **Figure 2**) leads to the conclusion that these gases partly must have been emitted also, which is elaborated on in 4.5.

As a major reason for the low O_2 PGC can be regarded, that the aeration method was not ideal. Wonschik (2017) suspected similar causes for the high CH_4 EM in his aerobic control treatments, when comparing them with much lower literature values. It became apparent that turning a windrow with the shovel of a wheel loader does not result in sufficient aeration. In turn, using a professional windrow turner, instead of a loader, would possibly be of advantage but poses other obstacles for on-farm application (see 4.2).

Overall, it can be concluded, that pH and temperature values indicated a successful CC process, but according to Maheshwari (2014) temporary excess moisture and low O_2 PGC challenge the ideal course of aerobic decomposition.

4.1.2 MC treatments

For comparability with literature values, the following methodological difference to Wonschik (2017) may be mentioned: temperature measurements in MC heaps were taken from about 0.5 m shallower below the surface in the present study. Wonschik (2017) measured approximately in the core of the heap, where temperatures may differ from the outer layers. Similar applies to PG measurements, which in this research were performed at 0.65 m and 1.5 m depth whereas Wonschik (2017) measured in 1.0 m depth. Therefore, an average value of both measurement depths was calculated (**Table 5**) to make the results comparable with those of Wonschik (2017).

Moisture levels of the MC treatments were within a suitable range throughout the entire composting process (see **Figure 3**), whereas temperature and O_2 PGC were partly quite high (53 – 58 °C, 0 – 14 vol%), compared to the suggestions of Witte (n. d.-a). Next to the above-mentioned differences in methodology, similar reasons can be suspected for both deviations from the MC method: The composting site was located a in windy region, which may have favoured O_2 intake into the MC heaps. In addition, composting took place during hot summer months in a region with more sun hours than at the German site used by Wonschik (2017) and, in addition, shading of the heaps was limited. In contrast, Witte (n. d.-a) advises to start composting either in spring or autumn and to place the heaps in partial shade. Due to these less-than-ideal circumstances, the compacted surface may not have been as gas-tight as expected. This could be determined by visual inspection of cracks in the surface (see 3.1.1). Next to site and season, the substrate composition with a rather narrow C/N (**Table 2**) may have increased heap temperatures due to high microbial activity. It is reasonable to assume that EM from MC treatments could have been lower, if circumstances (more gas-tight surface, less wind and sun, wider C/N) would have been more favourable.

Regarding the O_2 PGC an interesting observation was made: the average values of MC were in a similar range as the records from CC (**Table 5**) – even though CC was aerated frequently. This is consistent with the observations of Wonschik (2017), who explains this peculiarity with the differently conditioned metabolism of the microorganism, which in CC mainly consume externally supplied O_2, but other gases in anoxic MC milieus. In addition, hydrolysis is expected to take place in MC heaps, producing O_2 as side product, which can lead to comparably high O_2 values (Wonschik 2017).

Higher O_2 PGC (**Table 5**) than recommended by Witte (n. d.-a) may have decreased CH_4 PGC (Amlinger *et al.* 2008), which in MC1 & 2 were slightly low for MC composting (Wonschik 2017). Whereas in MC3 CH_4 PGC was about four times higher, compared to MC1 & 2 (**Figure 2** and **Table 5**). A possible reason for this deviation of MC3 can be seen in the different substrate composition (**Table 1**). Insufficient mixing of the start-substrate and wet pockets, resulting from pre rotted cereal straw, might have favoured CH_4 production (see 4.3). Moreover, a quite low C_{tot} and the resulting narrow C/N-ratio in the end-substrate (**Table 2**) illustrate the possibility for methanogenesis and C-losses through CH_4 EM.

CO_2 and H_2S PGC (**Table 5**) and progressions (**Figure 2**) however, both have been found to be very similar to the results of Wonschik (2017). Another similarity to Wonschik (2017) is, that the CO_2 PGC of the MC treatments were at the same level as the aerobic comparison treatment (CC before aeration).

NH_3 PGC showed a similar decreasing trend towards the end as H_2S (**Figure 2**). One approach to explain this is that these trends indicate the microbial consumption of both gases during chemolithoautotrophic CO_2-fixation (see 1.2) (Scott & Cavanaugh 2007; Witte n. d.-a). On the other hand, the decrease could also have been influenced by decreasing production towards the end of the composting process and possible losses to the environment. However, the latter cannot be verified clearly, as NH_3 and H_2S EM were only measured with a non-standardised and not statistically evaluated method (see 4.5 and **Table A 10**).

A visual observation (described in 3.1.1.) were fungal fruiting bodies *(Basidiomycota)* on the surface of the heaps, which also were observed by Wonschik (2017) and Ökoring (2019) during MC composting. The major discrepancy of the present study was that these fruiting bodies could be observed not only in the beginning of the process, but almost throughout the end, now and then. This may have been enhanced by additional inoculations with hay-tea during the composting process on 9th of June and 2nd of July (2.2.2). As Hubbe (2014) summarizes, some authors report positive effects of microbial inoculations of composts. However, the present study did not investigate the effects of hay-tea addition on the MC composts.

The comparison of the MC variants shows that MC1 with the highest N_{tot} values (**Table 2**), the better temperature and PGC ranges (**Table 5**), the lowest EM during composting and lower EM than MC2 during field application (**Figure 5**) can be considered the most successful MC treatment. The reason for this superiority can probably be seen in one of the few obvious differences, that there was no GM in the start-substrate, which also manifested in a wider C/N ratio. This observation should not lead to the general conclusion that GM is not suitable for MC, but special attention should be paid to the share in the mixture and the composition of GM from N-rich legumes and other components such as grasses.

Overall, it can be concluded that several observations as PGC, fungal fruiting bodies, temperatures and moisture contents were in a range considered favourable for the MC process. Some of them, such as O_2 or CH_4 PGC showed large variation between treatments and for others no clear statements can be given due to the lack of data. Thus, the MC process may not have been ideal in all treatments, but overall, it can be considered as satisfactory.

4.2 Nitrogen, phosphorus and carbon in the compost end-substrates

4.2.1 Nitrogen: the limiting factor in organic cropping systems

In contrast to conventional cropping systems, yields in organic agriculture are often limited by N availability. This is especially the case, if a farm is operated without livestock (Seufert *et al.* 2012). In the context of an organic farm and to keep the analysis manageable comparisons of the composting treatments were carried out on the basis of N_{tot} in the present research.

One key question of the present study was whether and to what extent it would be possible for the farm to replace externally purchased fertilizers by MC composting. When trying to compare the fertilisation value of composts with other commercial fertilisers, the question of N availability arises. So far, there is no consensus on how much of the N_{tot} from a compost substrate will be plant-available and especially not in what time frame after field application. In a literature review Boldrin *et al.* (2009) assume that 20 – 60 % of the N contained in compost can be credited for the substitution of other N-fertilizers. Hülsbergen (2019) describes somewhat more precisely that all NH_4-N and NO_3-N plus additional 5 % of N_{org} are plant-available within the first year. Since NO_3-N and N_{org} were not analysed in the present study, unfortunately no clear conclusion can be drawn regarding available N in the end-substrates. However, qualitative visual observations of WW plant growth in the beginning of the growing season 2021 possibly indicate that at least in MC1 there may have been a slightly higher immediate N-availability (see **Figure A 7**).

The proposed assumptions about N-availability of Hülsbergen (2019) and Boldrin *et al.* (2009) refer to aerobically composted biomasses, which raises the question to what extent this applies to MC. Nevertheless, it can be assumed that, compared to CC, the higher N_{tot} values of MC, indicate a possibly better long-term N-supply. In addition, the higher NH_4-N values in the MC end-substrates (**Table 2**) can indicate a good short-term N-supply. This is confirmed by the results of Wonschik (2017) who found higher levels of NH_4-N and NO_3-N in MC, which resulted in three times higher biomass growth of maize during growing trials, compared to CC (each mixed 1:1 with loamy soil). Due to the possibly high content of mineral N (N_{min}), MC seems more suitable as a fertiliser during the vegetation period, when N can be taken up in time by plants. To reduce the risk of leaching losses, fertilisation in late autumn should therefore rather be done with composts with lower N_{min} contents. In general, the varying and difficult-to-predict N-availability of composts poses a challenge in fertilisation management (Hülsbergen 2019). Thus, the N-availability and its accounting in the case of MC substrates need to be addressed by future research.

Overall, the lower N content in CC indicates higher N losses during the composting process. Potential reasons could be gaseous EM (N_2, N_2O and NH_3) and leakage (NO_3) (see 4.3). Coming back to N as the limiting factor in organic farming, MC appears to be more suitable than CC from the perspective of the N-fertilisation value.

4.2.2 Phosphorus: the upward limiting factor for nitrogen fertilisation

Due to the legal restrictions on P fertilisation (see 2.1) the farm was interested in finding out whether MC composting could be a useful tool to reduce P input by changing the type of fertiliser. Currently, the farm mainly uses CM with 5 – 6 kg P Mg^{-1} DM and a commercial product with 2 kg P Mg^{-1} DM (Ekoväx 2021). The substrate analyses (**Table 2**) indicate that MC end-substrates had a much lower P/N ratio (0.1) than the ones of CC (0.3) or pure CM (0.3). The difference between MC and CC can be explained by the higher loss of dry weight during CC which slightly increased the relative share of minerals, such as P, in the total mass. Therefore, it can be concluded that MC, with its higher N and lower P values, seems more suitable than CC for the goal of reducing P input with simultaneous N fertilisation.

Ekoväx, in comparison, has an even higher P/N ratio of 0.4. This fact makes Ekoväx seem even less suitable than CC or CM, but it must also be taken into account that the N availability differs in different types of fertilisers. Therefore, without a study of the plant availability of N in the various fertilisers, no definitive agronomic recommendation can be given. In order to test the P-input reduction potential of MC, an attempt could be made to gradually replace conventional fertiliser with MC substrates in subplots and to observe yield developments.

4.2.3 Carbon: the soil organic matter supplier?

The substrate analysis results (**Table 2**) confirm the literature findings of higher C-contents in MC substrates (Wonschik 2017; Witte n. d.-a). With a loss of about 22 % C_{tot} the C-degradation in CC was not as big as reported in the literature (Boldrin *et al.* 2009), but the higher C-degradation rate, compared to MC, could be confirmed.

While C_{tot} decreased, lignin – as the most persistent C-fraction in plant biomass (Eitinger & Schlegel 2007) – seems in particular to be recalcitrant to the processes in CC, as its share in the C-fractions almost doubled during decomposition (**Table 2**). In the MC treatments, on the other hand, the share of the lignin fraction increased only slightly, while C_{tot} did not change much at all. The finding that the CC end-substrate contained more stable C-fractions than MC therefore resulted mainly from the decrease in labile C-fractions in CC. However, as this is not an absolute statement of quantity, rather than a relative consideration of the fractions and their proportions, it should not be concluded that MC contained absolutely less stable C. On the contrary, as mentioned above, the C-pool remained relatively unchanged, which is reflected in the higher C_{tot} contents of MC.

Scientists are not yet in final agreement as to whether the addition of stable C fractions are more conducive to C-sequestration (Paulsen *et al.* 2009) or, following a more recent approach, whether labile C can be more easily be processed into stable SOM by soil microbes and therefore has greater positive effects on SOM content in the long term (Lehmann & Kleber 2015). To illustrate this debate: Thevenot *et al.* (2010) suggest that lignin fractions can even have shorter turnover times in soils than overall SOM, whereas Peltre *et al.* (2017) report the opposite; moreover, some of the mechanisms behind it are still unclear. However, if composts retain much C, which can thereby (at least intermediately) be bound in the SOM, some of otherwise earlier during composting emitted C can potentially be sequestered (Chadwick *et al.* 2011). A summary of studies suggests, that over a period of 4 – 12 years between 11 % – 45 % of the organic C applied to soil as compost remained as soil organic carbon (SOC) (Gilbert *et al.* 2020a). Considering this, the potential of C sequestration with C-rich compost substrates may be quite high, which could be interpreted as an advantage of reductive composting methods such as MC. Furthermore, if labile C fractions play an important role in nourishing soil microbes, MC could have an additional advantage. However, the comparably higher CO_2 EM of MC1 & 2 during field application (**Figure 5**) indicate that C may also be emitted, certainly due to microbial respiration. As Wonschik (2017) concluded, the significantly higher C content of the MC substrates may have led to CO_2-foliar-fertilisation and thus higher biomass growth, whereby these EM should not be understood exclusively as negative.

In general, from the results of the present study it can be concluded that the C-pool does not change much during reductive MC composting, but unfortunately the contribution of MC to SOM compared to CC could not clearly be assessed in the scope of the present study.

4.3 Factors influencing emission formation in the composts

One of the key factors, influencing EM dynamics in composts, is the management (Boldrin *et al.* 2009). Like elaborated in chapter 4.1 composting management was not always successful during the present study. To assess, which management-factors can be considered foremost influential to EM dynamics, some of them are discussed below.

4.3.1 C/N ratio

C and N of the composting substrates need to be in a suitable relation, as the available C must be microbially utilized, while most of the available N is stabilised (Saer *et al.* 2013). If there is a surplus in N, especially N-containing gases will be generated. Amlinger *et al.* (2008) conclude, that NH_3 and N_2O EM from composts are lowest, if the C/N ratio is greater than 25:1, while Jiang *et al.* (2011) come to the conclusion that a C/N ratio of 21:1 should lead to the lowest GHG EM. In turn, C/N ratios above 35:1 may result in limited decomposition and humification rates (Amlinger *et al.* 2008). Both Amlinger *et al.* (2008) and Jiang *et al.* (2011) refer to aerated composting methods, therefore it is not entirely clear how this applies to anoxic processes in MC.

In the present research C/N ratios of the start-substrates were in a wide range between 14 – 22:1 (**Table 2**), when jointly looking at results from different laboratories. Yet, the start-substrate compositions of MC1 & 2 and CC were very similar, and the large discrepancy between them can therefore rather be explained by different results from the two different laboratories: For example, the C/N ratios were between 14 – 16 according to Eurofins, but between 20 – 22 according to CU (**Table 2**). However, according to Jiang *et al.* (2011) and the analysis results from CU, C/N ratios were to be found in a rather suitable range for low EM. According to the results of Eurofins, the C/N ratios would need to be considered as too narrow. Since Eurofins gives high uncertainty rates for their measurements in the analysis reports, varying between 4 – 20 %, and furthermore the C/N-ratio is analysed according to a non-accredited method (see **Figure A 4**), the CU results could be considered more trustworthy in the case of C/N. Even though care was taken, sampling from a heterogeneous and bulky compost substrate is also a challenge that may have influenced the different laboratory results (see 2.3). These circumstances naturally made the interpretation of the data more difficult and reveal once again how divergent and sometimes even misleading results of different laboratories can be.

4.3.2 Heap temperature, moisture and oxygen levels

The discussion about optimal temperatures, to minimize EM from composting, is multifaceted since conclusions differ in literature and, on top of that, production of different gases are partly favoured by contrasting temperature conditions: Amlinger *et al.* (2008) suggest, that N_2O production is favoured by temperatures below 45 °C, but at the same time CH_4 and NH_3 EM are smallest below 45 °C. Therefore, the authors advise to maintain heap temperatures between 40 – 60 °C. Results from Beck-Friis *et al.* (2000), where highest N_2O EM were measured in composts with about 40 °C, support that partly. Explanation for this are the growing conditions of nitrifying bacteria *(Nitrosomonas and Nitrobacter)* between 5 – 40 °C (Beck-Friis *et al.* 2000).

In general, the by Amlinger *et al.* (2008) suggested temperature range was fulfilled in all treatments in average over the composting period (**Table 2**). A closer look at the temperature curve of CC reveals, that temperatures have been varying a lot: In the periods between 8th – 11th of July; 20th – 21st of July; 24th of July – 11th of August and 23rd of August until the end of composting, temperatures have been very close to 40 °C (± 3). During this entire period, from beginning of July until beginning of August, raised N_2O EM were observed, which support the findings of Amlinger *et al.* (2008) and Beck-Friis *et al.* (2000).

In addition, several rain events during July (especially in the beginning, see **Figure 3**), which resulted in standing water on the concrete floor and raising heap moisture content which in turn might have fuelled denitrification in CC, due to O_2 deficiency (Hellebrand 1998; Amlinger *et al.* 2008). These possibly waterlogged zones most likely have led to the raised CH_4 EM in all treatments during that period also (Beck-Friis *et al.* 2000). O_2 PGC in CC have not been considerably lower during this period (0.5 – 2.1 %vol, see **Figure 2**), but were in general very low (< 5 vol%) (Rynk *et al.* 1992).

Most authors are in agreement that CH_4 is produced by methanogenic microorganisms when O_2 is limited and anoxic or anaerobic zones occur (Beck-Friis *et al.* 2000; Jäckel *et al.* 2005; Cayuela *et al.* 2012) and Amlinger *et al.* (2008) moreover highlight the inverse relationship to N_2O production. This might explain the comparably higher CH_4 and lower N_2O results of the predominantly anoxic MC treatments. However, the CH_4 EM-peaks in CC occurred during the same phases when N_2O EM were highest (**Figure 3**), what stays in opposition to the assumption of their inverse relationship. This can possibly be reasoned with the changing and not always optimal milieu conditions during this period, caused by precipitation events and standing water on the concrete floor.

Ermolaev *et al.* (2019) highlight the importance of moisture content for CH_4 EM from composting, with the conclusion, that the most wet composts

(66 % moisture content) emitted most CH_4 and N_2O in their study. This can possibly explain as well the difference in CH_4 EM between the MC treatments: MC1, with 44 % moisture content, emitted about 20 % less CH_4 than MC2, with 55 % moisture content (**Table 5**).

In general, it can be concluded, that N_2O generation processes are very diverse and depend on different conditions, like oxygen, temperature, moisture and N-availability. Possibly, under changing milieu conditions – which are in particular caused by aeration events in CC (see 4.1.1) – a mixture of nitrification and denitrification processes, have led to the captured highest N_2O EM in the CC treatment.

CH_4 dynamics (methanogenesis and methanotrophis) in composts are so far not very well researched (Jäckel *et al.* 2005). But studies show that composts can provide suitable conditions for both CH_4 generation and oxidation (Jäckel *et al.* 2005). High moisture content and limited O_2 availability seem to be major factors favouring CH_4 EM from composts in general. However, the results of the present research do not provide consistent and strong evidence for this.

CO_2 is mainly produced through microbial respiration and therefore mainly depends on O_2 and C availability as well as on temperature and moisture conditions, which allow for microbial reproduction. Aeration events in CC have most likely led to the highest CO_2 EM of all treatments, even though EM released during aeration happenings themselves could not be captured, which may have further increased the total GHG flux.

4.4 Factors influencing emission formation in the field

In line with the approach of the present study, literature acknowledges that research about composting EM should as well integrate the examination of EM from the field after compost was applied to the field (Hao *et al.* 2004). Therefore, factors were identified, which can influence the formation of gases in the field after compost application.

4.4.1 Incorporation

In his theory of the Microbial Carbonisation Witte (n. d.-b) includes a tillage strategy for improving soil health through reductive processes, which includes an optimal incorporation depth for MC compost of about 0.15 m. The positive effects of this tillage strategy on yield potential could be confirmed by Ökoring (2019) and especially a farmer who was interviewed during the present research, who applies a tillage strategy based on Witte (n. d.-b) since several years. Hägler (2016) reports great agronomic successes and has attracted attention with this innovative soil cultivation, which is why several farmers are meanwhile following his example.

Nevertheless, in the present research the incorporation depth was much more shallow than the advice of Witte (n. d.-b) (see 2.2.3). Instead, the approach of regenerative agriculture was chosen (see 1), which requires that OM is always applied on top of the soil, following nature's example (Näser 2020). However, WW was seeded into the bare soil one day after compost application (2.2.3), which reveals a misconception of the RA approach, as OM should always be applied into standing crops or cover-crops to be incorporated by a well-working soil-life (Näser 2020).

Farmers, interviewed during the present research, are following various strategies of compost application with many of them preferring the RA strategy (see 3.4.7). In summary, it can be concluded that not following the advice of Witte (n. d.-b) and applying the composts very shallowly can have influenced EM progression. Nevertheless, comparability between the treatments is guaranteed, as they were all incorporated the same way.

4.4.2 Soil moisture, N and C availability

Literature describes soil moisture, oxygen, N and C availability as key controlling factors for N_2O EM generation from soils (Hansen *et al.* 2019; Singh *et al.* 2019). Like in composts, denitrification and nitrification processes are main drivers for N_2O generation in soils (Firestone & Davidson 1989). Hansen *et al.* (2019) highlight denitrification as the main source, especially under the condition of high C-availability. A peak of N_2O EM, captured on 26th of September after a heavy rain event the day before, with a resulting rapid increase in soil moisture, illustrates this very well (**Figure 4**). Since this peak occurred only three days after compost application, and under later on continuing increases of soil moisture no N_2O peak with similar extent have been observed again, it can be assumed that this peak was so high because the fresh biomass provided much available N and C (Peigné & Girardin 2004). This is supported by MC1 & 2 both showing the highest EM peaks while having high C_{tot} and N_{tot} contents in the end-substrate (**Table 2**). In general, such peaks illustrate the possible risk of high N_2O EM (after N-fertilization) which can be difficult to predict (Kang *et al.* 2021). Nevertheless, the possible contribution of background EM from SOM derived N can play a role here, since the rather alkaline soil pH of 7.3 (3.2.1) may have provided suitable conditions for denitrification (Hansen *et al.* 2019).

CH_4 dynamics depend mainly on soil moisture content and C availability, which provide suitable conditions for methanogenic or methanotrophic microorganisms (Jäckel *et al.* 2005; Kang *et al.* 2021). The interesting result of the MC treatments showing very low or even negative CH_4 EM sums (**Table**

6) indicate, that CH_4 oxidation must have outweighed methanogenesis in those treatments. However, it is not entirely clear why CC showed higher CH_4 EM than the MC treatments. According to Kang *et al.* (2021), the higher NH_4-N contents of the MC substrates (**Table 2**) could indicate that methanogenesis was suppressed. Moreover, available C might have fuelled microbial methane consumption in the upper soil layers of the MC treatments. Compared to CC, higher rates of soluble C, especially in MC3 (**Table A 13**) which showed a negative CH_4 EM sum, can be considered causal for this also. Additionally, it is important to consider the big standard errors, which accompany the CH_4 EM values, especially in MC, and illustrate the heterogeneity of the measurements between single chambers (**Figure 4** and **Table 6**).

CO_2 EM showed smaller relative differences between MC and CC treatments than the other GHG (**Table 6**) but were located on not inconsiderably high levels. Higher CO_2 EM of MC1 & 2 support the assumption that the high availabilities of C and N enhanced microbial decomposition processes. That an increase in CO_2 concentration can substantially enhance photosynthetic productivity of plants was shown in several studies (Gifford 2004; Haworth *et al.* 2015; Arneth *et al.* 2019). Moreover, CO_2 fertilization can increase water-use efficiency (Haworth *et al.* 2015). Therefore, it can be hypothesised that CO_2 EM from field application of compost is perceived as more positive than when it is generated during composting, where it cannot be directly taken up by a crop stand. This can be interpreted as advantage for reductive composting methods like MC, which emitted less CO_2 during composting and more during field application, compared to CC (**Table 7**).

4.5 The contributions of pore gas measurements

Not only to evaluate the successfulness of a composting process but as well to examine the possible sources and causes of emitted gases from the heap, PG measurements can be very useful. For instance Beck-Friis *et al.* (2000) showed that composts with high N_2O PGC had also high N_2O EM. But caution is needed in drawing direct conclusions from PGC to EM, as other studies have shown that high PGC did not always materialize in high EM (Hao *et al.* 2001).

Gas fluxes are mainly affected by the concentration gradient and the diffusivity between the PGC and the ambient air. In CC, diffusivity is partly very high because the windrow is frequently aerated. In turn, aeration promotes microbial activity, which raises the PGC and creates the possibility for EM. Hence, the PGC before and after aeration of CC can give some indications about possible EM during the aeration events, which could technically not be detected because measurements could not be performed during aeration.

In MC, in contrast, the diffusivity is likely to be lower, due to the compacted surface. Therefore, higher PGC should be acceptable without causing bigger EM than in CC with higher diffusivity. The comparably high PGC in MC, combined with lower overall EM than in CC, support the assumption that the surface constitution may be a successful measure to decrease the diffusivity.

An example of EM that may have not been captured by EM measurements in CC is CH_4. Even though the average CH_4 PGC in 0.65 m depth have been similar in MC and CC treatments (**Table 5**), captured CH_4 EM have been about 40 % lower in CC. Moreover, EM and PGC of CH_4 showed a significant positive correlation in CC (**Table A 12**) and aeration happenings decreased CH_4 PGC by 3 % in average (**Table 5**). These observations strengthen that in CC a direct relationship between PGC and EM exists. Furthermore, other studies have reported CH_4 EM from aerated treatments in even greater dimensions than measured during this research (Hao *et al.* 2004; Saer *et al.* 2013).

Similar connections can be seen in H_2S and NH_3 PGC which decreased by 56 and 105 ppm, respectively, during an average aeration happening. Both gases can be odour pollutants in the direct surrounding of the composting site and NH_3 also is a major contributor to the eutrophication of water bodies (Saer *et al.* 2013). Moreover, the risk exists that NH_3 can be converted to N_2O, which will be elaborated on further below. In addition, the hypothesis that not all N_2O EM of CC were captured by EM measurements, is supported by a literature review of Saer *et al.* (2013), in which they found much higher EM values from aerated treatments than recorded in the present research.

In the following, some indications will be given of what possible links might exist between PGC and EM in CC and MC. This is done without claiming to be exhaustive, as such dynamics and interactions are very diverse, especially regarding the N cycle (Butterbach-Bahl *et al.* 2013).

Possible links between pore gas concentrations and emissions in MC

N_2O EM were negatively correlated with CO_2, NH_3 and H_2S PGC (**Table A 11**). The negative correlation between NH_3 PGC and N_2O EM stays in opposition to the assumption that available NH_3 can fuel N_2O generation in composts by ammonia-oxidation, but on the other hand, high NH_3 availability can also inhibit nitrification, resulting in low N_2O EM (Amlinger *et al.* 2008). Under anoxic conditions, the negative relationship of both NH_3 and H_2S PGC with N_2O EM could support the assumption of Witte (n. d.-a) that N and H are used as electron acceptors by microbes during chemolithoautotrophic CO_2-fixation (see 1.2) (Scott & Cavanaugh 2007).

On the other hand, N_2O EM were positively correlated with high O_2 PGC (**Table A 11**), which ideally is supposed to be below 1 vol% (Witte n. d.-a).

Therefore, the hypothesis of Witte can be supported, that ideal MC heaps (with low O_2 PGC) are supposed to emit little N_2O. Even though the MC method might have not been applied perfectly in the present research (see 4.1.2), the comparably low N_2O EM in both MC treatments (**Table 5**) are supporting this assumption. The partly raising O_2 PGC in both MC1 & 2 (**Table A 11**) can therefore be interpreted as reason for the slightly raising N_2O EM during the late measurement phase (**Figure 3**).

CH_4 EM showed no significant correlation with any PG but in MC1 CH_4 EM showed a positive correlation with N_2O EM (**Table A 11**). This illustrates how difficult it is to predict CH_4 generation and EM from MC composting. The correlation with N_2O EM was significant but not very strong (0.552). Nevertheless, it shows that there can be a link between EM of different GHG.

Possible links between pore gas concentrations and emissions in CC

The above-mentioned positive correlation between O_2 PGC and N_2O EM was confirmed in CC (**Table A 12**). This observation is in line with Amlinger *et al.* (2008), Hellebrand (1998) and Jiang *et al.* (2011) and highlights the discussion about optimum aeration frequencies in CC treatments, respectively the possible advantages of reductive composting regarding low N_2O EM. Bai *et al.* (2020) also reported greater N_2O EM from windrow composting of manures (like CC), compared with stockpiling them (may be comparable to MC). Other studies come to similar conclusions (Parkinson *et al.* 2004; Chadwick *et al.* 2011).

The until the end continuously high NH_3 PGC of CC (**Figure 2**) have possibly not only contributed to NH_3 EM but to the generation of N_2O EM through oxidation of NH_3 (Amlinger *et al.* 2008; Bai *et al.* 2020). Statistically unevaluated gas measurements of the EM measurement chamber-air, carried out with the portable gas analyser X-am® 7000 following the regular gas sampling, indicated that CC may have emitted about twice as much NH_3 as MC. (However, these results are not very reliable and are therefore not elaborated in chapter 3 but can be reviewed in appendix in **Table A 10**.)

According to Amlinger *et al.* (2008), NH_3 generation during composting is hard to regulate, but is usually increased by aeration. Peigné and Girardin (2004) describe, that NH_3 is the main source of N-losses during manure composting and that several other studies confirm that NH_3 EM are higher for aerobic treatments moreover. This strengthens the assumption that the higher N-losses of CC, compared to MC, mainly resulted from NH_3 EM and were therefore not detected by the regular N_2O EM measurements. Hence, the possibly lower NH_3 EM can be interpreted as an advantage of reductive composting.

CH_4 EM in CC correlated with high CO_2 and CH_4 and low O_2 PGC (AA) (**Table A 12**). Since CH_4 is mainly formed under O_2-limited conditions (Peigné

& Girardin 2004) and O_2 PGC was very low for an aerated treatment, it supports the hypothesis, that CH_4 EM can be reduced by more frequent aeration (Amlinger *et al.* 2008; Jiang *et al.* 2011), which in turn stimulates CO_2 production. A study of Beck-Friis *et al.* (2000), during which EM and PGC measurements were performed on composts, confirms this negative correlation of O_2 and CH_4.

CO_2 EM in CC were also negatively correlated with O_2 PGC (before aeration), which is logical as O_2 is needed for microbial CO_2 generation. By implication, this supports that O_2 PGC was often too low, which possibly limited CO_2 generation. If CO_2 is the favoured product (in opposition to CH_4), more frequent and sufficient aeration may solve this issue (Amlinger *et al.* 2008; Jiang *et al.* 2011).

4.6 Global warming potential emission factors

Often, studies about waste management do not mention explicitly which GWP they have assigned for N_2O and CH_4. Older studies, like Pattey *et al.* (2005) or Boldrin *et al.* (2009) have used GWP_{100} 23 or 25 for CH_4, 296 or 298 for N_2O, respectively; biogenic CO_2 was assigned GWP zero. Recent studies, like Bai *et al.* (2020) have used GWP_{100} 28 and 265 for CH_4 and N_2O, respectively; biogenic CO_2 was not included in GWP assessment.

A review about life-cycle-assessment (LCA) studies in waste management acknowledges, that there is no consistency in literature about the GWP of biogenic CO_2 (Christensen *et al.* 2009). Some consider biogenic CO_2 to have no global warming contribution and others assign it to have GWP = 1. Christensen *et al.* (2009) concluded, “that assigning global warming contributions to biogenic carbon dioxide in waste management can be done both ways (biogenic neutral, biogenic counts)” (p. 715). Similar applies to the CO_2 EM from compost application to the field. Consequently, in the present research GWP_{100} factors were chosen according to the recently pre-published 6^{th} assessment report of the IPCC: 27.2 for CH_4 from non-fossil origin, 273.0 for N_2O and 1.0 for CO_2 (IPCC 2021).

Since the focus of the present research lies on comparing two composting techniques with obviously different C-volatilisation rates, it was decided to include CO_2 EM in the GWP assessment. The RA-focus on the C-retention potential of MC substrates cannot really be assessed in the scope of this study, but one hypothesis could be that C applied to the field, rather than being previously emitted during composting, has a greater chance of forming organo-mineral complexes or being metabolised by soil microorganisms, thereby possibly contribute to SOM enhancement. Additionally, in the case of compost being applied into a growing crop, it could be suggested to perceive CO_2 EM as fertilization (4.4.2), like Wonschik (2017) did. Hence, it could be concluded that CO_2 being emitted is more of an advantage when emitted after field application, compared to EM from composting.

The above illustrates how important it can be to include CO_2 EM into the climate assessment for a fair comparison between composting treatments. Moreover, against the background of the urgent need to reduce GHG EM as early as possible, including CO_2 into the assessment may be considered reasonable. This is because every GHG molecule that is not released – regardless of whether it is of biogenic or geogenic origin – can potentially contribute to immediate climate change mitigation. However, it must be acknowledged that the present study did not comprise any long-term monitoring and therefore it cannot be assessed how EM behaved after the first 11 weeks of field application. Furthermore, the comparably large share of CH_4 EM in MC treatments during composting show for example how misleading it can be to judge the climate impact of a composting method on only one gas, like for instance Egger (2019) did.

4.7 Methodological limitations regarding emissions

4.7.1 Emission measurement methodology issues

In other studies, where EM from composting have been measured, mostly closed measurement systems were used, which enclose a certain amount of substrate, e. g. a whole composting bin (Pattey *et al.* 2005; Cayuela *et al.* 2012). Such approaches provide a degree of certainty that all EM, released by a specific substrate amount, can be captured. Not so in the case of the present research, where EM have been measured on only three specific surface-areas on each compost heap (see 2.7.1).

To measure and assess EM from soils, EM are usually presented in relation to a reference area (EM ha^{-1}) (Kasimir-Klemedtsson *et al.* 1997; Erhart *et al.* 2016; Hansen *et al.* 2019). However, for the assessment of the climate impact of compost substrates, it seems more appropriate to express the EM in relation to the substrate volume or mass (EM Mg^{-1}) – especially if EM from composting and EM from compost application of a certain amount are to be compared. To express the composting EM in relation to the compost mass, the following assumptions were made in the present study: The measured EM originate only from the volume vertically below the measurement chamber (surface area multiplied by the compost height); and a specific weight of the substrate was also assumed (see 2.7.2). The first assumption does not take into account that EM do not only rise vertically in the heap, and they can therefore originate from a much larger or smaller region. Hence it is not entirely clear in which way these assumptions might have biased the results, but they may have led to greater variability.

The NSS chamber methodology (2.7.1) used in the present study tends to underestimate EM fluxes (Venterea 2010). This is in particular the case for CO_2, as the chambers were rather constructed for N_2O measurements, and a high (CO_2) EM flux of the composts could have saturated the headspace of the chamber more quickly. To account for these issues, the chamber-closing-time was chosen shorter than usually applied on soils but was possibly still too long for the relatively large CO_2 EM fluxes (see 2.7.1). Nevertheless, this was considered the best possible compromise for measuring all GHG at the same time. Moreover, the insertion depth of the collars, which is described by Rochette (2011) to avoid lateral diffusion (leakage) in loose substrates, could unfortunately not be achieved during all compost measurements. This circumstance increases the uncertainty of the measured EM quantity and may have contributed to the underestimation of some fluxes.

Since the surface condition of MC heaps is very important for the success of the process and the EM progression (Witte n. d.-a), inserting EM measurement collars can have negative influence on success. This is because the insertion of the stainless-steel plates changes the substrate structure and chimney effects can occur at these sources of interference, through which gases can escape in turn. The problem was amplified by shrinkage cracks, that occurred during the composting at the collar-substrate interface, when the MC heaps were drying out at the surface. These shrinkage cracks, which are also known from soil EM measurements (Rochette 2011), can affect the gas exchange. It can be assumed therefore that the collar method used in this research proved not to be very suitable for MC composts, as their sensitive surface can be severely affected. Chimney-effects through the collar-substrate interface might have led to additional gas fluxes, which might not have occurred without manipulating the surface.

A special issue in measuring EM from CC was, that it was not possible to measure EM during aeration happenings since the chambers would have needed to stay on top of the undisturbed pile during the measurement interval (see 2.7.1). The usual observations, such as odours and steam during the turning of CC, and the often-decreased PGC afterwards (**Table 5**) suggest that not all EM fluxes from this treatment were captured. In turn, this limits the fair comparability with the MC treatments, where no mechanical disturbance is required, and it is therefore very likely that EM do not occur as episodically in MC.

To avoid disturbance of the MC's surfaces during EM measurements, a scaffold was installed over the MC heaps (see **Figure 1**). This was not feasible in CC because space was needed around the windrow for aeration machinery. Therefore, it was necessary to step on the CC substrate for EM measurements. This might have led to temporary but in general unfavourable compaction zones next to the measurement chambers. This, in turn might have influenced EM dynamics of CC negatively.

The above-mentioned issues in measuring EM without causing major biases under open on-farm composting conditions implicate the need for more suitable measurement methodologies. Amon *et al.* (1996) have developed a mobile and large-scaled open dynamic chamber to determine EM rates from agriculture. With such a mobile chamber it would be possible to temporarily enclose an entire compost heap. Similar approaches have been chosen by Parkinson *et al.* (2004) to measure EM from composting manures. Such approaches are of particular interest with regard to MC as this composting method is dependent on solar radiation and other environmental influences. Therefore, MC composting cannot be carried out in permanently closed monitoring systems, like used in closed composting studies (Ermolaev *et al.* 2019). Another, less invasive approach would be to measure EM in the ambient air, surrounding the compost, like Bai *et al.* (2020) did in a very recent study, using open-path Fourier transform infrared (OP – FTIR) technology. Such approaches also allow to better capture the EM during mechanical turning processes of aerated treatments.

In conclusion, these alternative EM measurement methods, which possibly have less influence on the composting process itself and its environmental conditions, need to be tested and evaluated for their suitability for on-farm composting, especially MC. Unfortunately, this was not possible within the scope and resources of the present study. The NSS chamber methodology may not have been perfect from the beginning but was the only method available. The more extensive above-mentioned problems, that made the method seem less than ideal, arose during the measurements and were detected too late to change the set-up. Nevertheless, it is an advantage that the same EM measurement method was used for composting and field EM, which increases their comparability.

4.7.2 Analysis issues and corrective calculations

During the composting phase 20 EM measurement occasions were performed within 79 days. During the field application phase, on the other hand, only 8 measurements were distributed over a very similar timespan of 78 days. This higher resolution during composting was reasoned in the uncertainty of EM progression from composting and the lower resolution during field measurements, on the other hand, in budget limitations. Nevertheless, this difference in resolution must be emphasized and considered when assessing the results, because consequently the field EM sums are more dependent on the EM-trend calculations than the composting EM. This can lead to peaks, following or followed by longer measurement pauses, having a very strong influence on the EM sum of the entire period. The large influence of exceptionally strong peak values can be seen in the N_2O measurements on 26th of September (see 3.2.2.1). The influence of long measurement pauses, on the other hand, is evident in the last CH_4 measurement, which was above average, but not exceptionally high. Nevertheless, it had a large influence due to the previous measurement pause of almost one month (see **Figure 4**).

During the gas analysis in the GC some samples showed unexpected high concentrations of CH_4, CO_2 and N_2O. These concentrations were beyond the standard range of the laboratory at CU. Therefore, additional standard-samples were added, to extend the measurement range of the GC. For CH_4 the maximum calibration value was at 1 000 ppm, for CO_2 at 30 000 ppm and for N_2O at 2 ppm. The different gas standard concentrations from the SLU and CU laboratories have led to need of corrective calculations, especially in the field EM. De Klein *et al.* (2020a) address the need for such statistical data transformations, which, however, do not affect the integrity of the data. Therefore, it is assumed that the corrections have made the results more trustworthy.

4.7.3 The limited comparability of compost and field emissions

The limited comparability of compost and field emissions was already touched upon in chapter 3.3. A few words of explanation should therefore be added here.

Since an unfertilised control plot, to compare with the compost treatments, would have exceeded the capacities of the present study, it is not possible to clearly distinguish how much EM resulted from the compost application or from the background EM of the soil itself. For the example of N_2O, as a review of Hansen *et al.* (2019) concludes, the main driver for N_2O EM in organically farmed soils is not fertilisation but N that is derived from SOM. The absolute values of the field EM can therefore not simply be added to the EM from composting, as this would lead to overestimation of the field EM. Furthermore, only the period of the first 11 weeks after application was considered, which excludes the necessary long-term perspective. For N_2O it can be assumed that most of the EM were already formed at the beginning of the application, and the CH_4 EM were so small that they are almost negligible, whereas for CO_2 – despite a falling trend – the development over a longer period of time seems less clear (see **Figure 4**).

Nevertheless, differences between the treatments can be determined even without knowledge of the background EM. However, these differences would be lost in a combined GHG balance of composting and field EM, as the absolute field EM exceed the composting EM many times over. Therefore, the informative value of a joined GHG-balance is limited and it was decided to present them separately.

In **Table 7** it was shown that EM can also be expressed per kg N which was applied with compost to the field. Due to different N_{tot} contents of the compost substrates (which must be due to higher, but only partly detected N-losses in CC, see 4.5) this seems like a fairer comparison. However, this consideration shows that MC composts can provide N with lower GHG EM than CC, despite the possibly big background EM still masking the large EM savings during composting. It can be concluded that there could be clearer advantages for MC, if background EM could be excluded and the EM were expressed in relation to the N content of the substrate.

4.8 The influence of machinery related emissions

Since the machinery labour demand was so different in CC and MC (**Table 3**) and to achieve a more holistic assessment, it would be important to add fossil fuel related EM from diesel driven machinery to the composting EM. A valid assessment was beyond the scope of this thesis, but nevertheless, to give an indication in which range fossil fuel EM of composting operations can be, a brief literature review and calculation resulted in the following numbers.

Using a wheel loader for aerating CC, like in this farm case, fossil EM from diesel combustion and provision are in a range of 6.4 – 17.1 kg $CO_{2\text{-eq}}$ Mg^{-1} (Fruergaard *et al.* 2009; Frey *et al.* 2010; Maskinkalkylgruppen 2019). Depending on the efficiency of a professional composting facility, EM from diesel combustion and provision of a windrow turner (commonly used alternative to a wheel loader) can be found in a range of 0.7 – 20.9 kg $CO_{2\text{-eq}}$ Mg^{-1} (Hao *et al.* 2001; Komilis & Ham 2004; Boldrin *et al.* 2009; Fruergaard *et al.* 2009). These wide ranges given an indication how difficult it can be to judge the fossil fuel related EM of CC.

For 10 Mg of compost being applied to one hectare, $CO_{2\text{-eq}}$ in a range of about 7 – 200 kg Mg^{-1} would hypothetically need to be added, in the case of aerated composts (CC). In relation to the direct geogenic EM (CH_4 and N_2O), originating from the composting process itself and the first 11 weeks of field application (CC: 682 kg $CO_{2\text{-eq}}$ ha^{-1}), the fossil fuel related EM could be in the range of additional 1 – 30 % for aerated treatments. Hence, the results of the present research highlight the importance to include machinery related EM into climate impact assessments, when comparing CC methods with less machinery labour demanding methods, like MC.

4.9 Economic assessment of MC and CC

The high machinery demand of CC, shown in **Table 3** and **Table 4**, is obviously due to the frequent need of mechanical aeration with the wheel loader, which in MC is not required at all. The following two restrictions need to be mentioned here: firstly, turning windrows with loaders is not considered to be the most efficient method, even though it can be considered as the most likely being used in smaller on-farm composting operations; and secondly, the experimental scale, with only 7 m^3 of CC, and long travel times to and from the place of composting have reduced the efficiency furthermore, since economies of scale play an important role in the efficiency of composting operations (Rynk *et al.* 1992). Moreover, machinery use for the maceration process of MC and the pre-treatment of start-substrates were not recorded separately and therefore are not included in the calculation in **Table 3**. But since these steps are not always mandatory for MC and otherwise this machinery input could be equated with the first windrow turning events of a comparable CC treatment, this would possibly not cause such a big difference in efficiency.

Rynk *et al.* (1992) describe working capacities of tractor-driven windrow turners in a range of 306 – 917 m^3 h^{-1} and front-loader windrow-turning with capacities of about 11 – 32 m^3 h^{-1}. These literature values correspond to about the tenfold of the recorded capacities in the present research, which were 1.6 m^3 h^{-1} (**Table 3**). In a study about tractor-drawn windrow turner performance, Zemánek (2002) comes to the conclusion, that they never reached the optimal, by the manufacturer declared, performance. The realistic performance was to be found in a range of about 10 % of the declared capacity only, which was 71-197 m^3 h^{-1} in this study. In addition, for a realistic assessment, the travel time to and from the composting site must be taken into account, as in the case of BO, where the composting site was not centrally located on the farm. Furthermore, given the required investment volume of 10.000 – 100.000 $ for a windrow turner (Rynk *et al.* 1992), wheel loaders, which are mostly available on farms anyway, seem to be a good alternative for smaller on-farm composting operations. This underlines the advantages of MC composting, which can easily be implemented with available equipment, a sufficient machinery efficiency and without compromising composting quality. Therefore, the claim made by Wonschik (2017), that MC can be considered as a very economical biomass waste treatment method, can be confirmed by the present research, in the context of on-farm composting.

4.10 The added value of capturing farmers' perceptions

In retrospective, the inclusion of a social science element (2.9) into this research was perceived very valuable in order to embed realistic and long-term experiences about MC composting, to understand and contextualise mistakes and successes of the MC application during this research and to gain more knowledge about farmers' needs and questions for future research.

TIFI, chosen as interview method, proved to be very suitable and successful. Through the in advance of the interviews prepared but very flexible interview guide it was possible to capture each farmers' view in a very short time, compared to the detailed amount of information, which was delivered by the interviewee. The themes and sub-questions were slightly adjusted after each interview to possibly improve the conversation flow of the next one. This can be seen as bias, as not every interview was conducted identically. However, for the mere purpose of gaining knowledge, this bias seems negligible, and moreover, each interview situation was in a very different setting. Therefore, flexibility and thorough preparation was more important than a fixed interview scheme. Although it was challenging for the interviewer to take notes, while actively listen and at the same time steering the interview towards the next topic, taking notes during the interview proved to be a very time efficient way, to accurately record the farmers perceptions in detail. This confirms the opinion of Halcomb and Davidson (2005), that field notes are most important.

Meeting farmers in person within their personal surrounding of the farm and partly conducting the interview at the composting site turned out to be very intensive in the wealth of information. Unfortunately, only two of the interviews could have been conducted in person on site, due to time and resource limitations and moreover the restrictions during the pandemic situation in early 2021. An advantage of telephone or video-call interviews was that taking notes was much easier within the personal surrounding of the interviewers' office. Taking these heterogeneous interview situations into account, the additional audio recording of each interview proved to be very helpful to be able to refine the notes and to reconstruct complex statements in retrospect, when writing the summary draft.

The feedback loop, in which the final written summary of the interview was prepared jointly with the interviewee, proved very helpful in correcting small misunderstandings and deepening the insights. All interviewed farmers have been very openminded and motivated to contribute to the success of this research and valued the transparency of the TIFI method. Most of them even provided additional information, like substrate analysis results or pictures from composting, which enhanced the density of information.

In conclusion, TIFI was experienced as a very helpful and flexible tool for the intended purpose of efficiently obtaining information about farmers perceptions on composting. The data collected can be regarded very credible and useful.

4.11 Continuative questions and future research

In this chapter, questions which have arisen during the present research, but unfortunately could not be answered within the scope of this study, will be recommended to be addressed by future research.

Better and more comprehensive EM measurements

In order to not bias the composting process and thus the EM dynamics, and at the same time to enable the capturing of all EM – even during aeration phases – methods such as those used in Bai et al. (2020) or Amon et al. (1996) must be tested for their suitability and significance for on-farm composting.

Although the present study was able to make a contribution to the assessment of MC composting by considering N_2O EM as an important GHG for the first time, it is nevertheless important to consider gases with even larger GWP – like volatile organic compounds (according to Peigné and Girardin (2004) VOC can have the impact of about 2000 $CO_{2\text{-eq}}$). VOC can be major EM from composting and furthermore have toxic effects on humans (Krzymien *et al.* 1999; Peigné & Girardin 2004; Saldarriaga *et al.* 2014; Khosravi & Jobson 2020). Therefore, future studies about MC composting considering VOC are recommended.

As discussed in 4.5, ammonia might have been a major contributor to N-losses, especially in CC. Therefore, it is suggested that in future studies comparing different composting methods, NH_3 EM should also be measured.

Measuring hydrogen PGC and assessing hydrogen translocation

In order to better assess the successfulness of the MC process, H^+ PGC should be measured, like Wonschik (2017) did. This could give better indications about chemolithoautotrophic CO_2-fixation, during which H^+ is used as an energy source. Moreover, the pathway of H^+ translocation from the surface, where hydrolysis shall take place (Witte n. d.-a), into the rest of the MC heap needs to be researched.

Microbiological assessments and effects on soil health

There is not yet much statistically relevant and meaningful data from measurements of microbial differences between MC and CC substrates – nor is there reliable data on the effects of reductive and aerobic composting methods on soil life and health, including their contribution to increasing SOM. It emerged from the farmers' interviews that there is a great need for such data, as farmers want to know to what extent a certain type of composting leads to an improvement in soil health or not. Furthermore, in a RA context, it could be interesting what the influence of soil life on C-sequestration and EM is when MC substrate is applied to a standing crop and not incorporated.

Agronomic effects of MC composting

The importance of lignin for MC composting implicates that WC can be a suitable start-substrate component. WC could potentially result from agroforestry systems, which can produce major lignin-containing excess biomasses. In turn, arable strips between the woody strips could benefit from these C-rich substrates. Thus, the synergies between agroforestry and MC should be explored in future research.

As there are still uncertainties about the long- and short-term N-availability of MC substrates, cropping trials with yield measurements over several years should be carried out with MC substrates. The effect of C-rich MC substrates should also be investigated when applied into legume-rich cover crop stands or clover-grass. This is because there is a possibility that legume-N will be microbially bound with the compost C. Thus, the possible N-lock, that can limit the N-availability in C-rich substrates, can be reduced and legume N is better preserved for the next main crop.

Last, but not least the MC tillage strategy of Witte (n. d.-b) in combination with MC composting should be investigated further, since some authors reported increases in yields (Hägler 2016; Ökoring 2019).

Legal regulations and policy recommendations

How MC can be officially recognised by authorities as a composting method and included and evaluated in legal fertilization and composting regulations need to be investigated and clarified for the practical applicability of the method in regional contexts.

5 Conclusions

The present study suggests that reductive composting (MC) can provide substrates with higher N and C contents compared to aerobic windrow composting (CC). Therefore, MC appears to be promising for on-farm use in a RA context with a focus on soil health. However, the long-term effects on the soil were not investigated in the present study and need further attention.

MC was found to be a very cost-efficient on-farm composting method, requiring less labour than CC and is therefore particularly suitable for processing and refining larger quantities of biomasses such as manure. The reduced use of machinery is also associated with lower fossil fuel EM. On the other hand, CC was found to be less feasible with existing farm machinery and poor management can substantially increase EM. CC thus seems to be feasible only for farms willing to invest in special windrow turning machinery.

The present research was able to make an important contribution to the assessment of the climate impact of MC composting by measuring N_2O EM for the first time. The results suggest that this compound was three times lower on a weight basis during MC composting compared to CC. Another novelty was the extension of the EM measurements to the field application phase, showing that this extended view can substantially increase the total climate impact of what at first sight appears to be a climate friendly composting process. On a weight basis, MC showed lower GHG EM during composting, compared to CC. This advantage, however, was offset by higher EM in the field during the first 11 weeks after application.

In addition, GHG balances are highly dependent on the appropriateness of the measurement-methodology, the period under consideration and the reference unit in which the EM are expressed. As higher N-losses were indicated in CC during composting, MC emitted less GHG overall per kg N applied with compost to the field. It was therefore not entirely clear whether MC or CC performed better in terms of GHG EM as this depends on different variables.

Integrating farmers' perceptions into a predominantly natural science-based study was also non-trivial and important impulses for future research could be identified through the interviews, such as investigating the effect of MC substrates on soil health.

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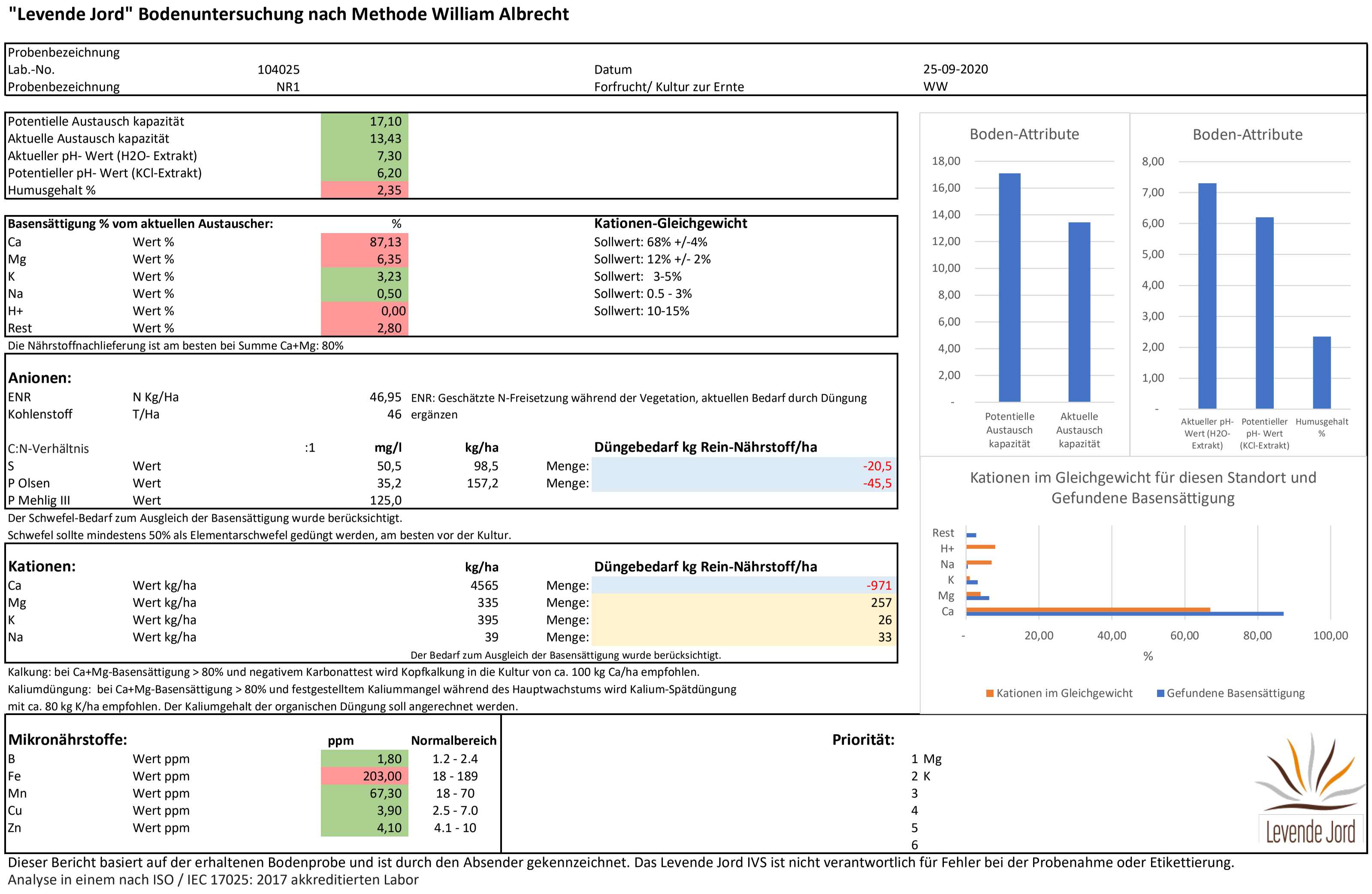
Appendix



"Levende Jord" Bodenuntersuchung nach Methode William Albrecht

Probenbezeichnung			
Lab.-No.	104025	Datum	25-09-2020
Probenbezeichnung	NR1	Forfrucht/ Kultur zur Ernte	WW

Potentielle Austausch kapazität	17,10
Aktuelle Austausch kapazität	13,43
Aktueller pH- Wert (H2O- Extrakt)	7,30
Potentieller pH- Wert (KCl-Extrakt)	6,20
Humusgehalt %	2,35

Basensättigung % vom aktuellen Austauscher:		%	**Kationen-Gleichgewicht**
Ca	Wert %	87,13	Sollwert: 68% +/-4%
Mg	Wert %	6,35	Sollwert: 12% +/- 2%
K	Wert %	3,23	Sollwert: 3-5%
Na	Wert %	0,50	Sollwert: 0.5 - 3%
H+	Wert %	0,00	Sollwert: 10-15%
Rest	Wert %	2,80	

Die Nährstoffnachlieferung ist am besten bei Summe Ca+Mg: 80%

Anionen:

ENR	N Kg/Ha		46,95	ENR: Geschätzte N-Freisetzung während der Vegetation, aktuellen Bedarf durch Düngung		
Kohlenstoff	T/Ha		46	ergänzen		
C:N-Verhältnis		:1	**mg/l**	**kg/ha**	**Düngebedarf kg Rein-Nährstoff/ha**	
S	Wert		50,5	98,5	Menge:	-20,5
P Olsen	Wert		35,2	157,2	Menge:	-45,5
P Mehlig III	Wert		125,0			

Der Schwefel-Bedarf zum Ausgleich der Basensättigung wurde berücksichtigt.
Schwefel sollte mindestens 50% als Elementarschwefel gedüngt werden, am besten vor der Kultur.

Kationen:		**kg/ha**	**Düngebedarf kg Rein-Nährstoff/ha**	
Ca	Wert kg/ha	4565	Menge:	-971
Mg	Wert kg/ha	335	Menge:	257
K	Wert kg/ha	395	Menge:	26
Na	Wert kg/ha	39	Menge:	33

Der Bedarf zum Ausgleich der Basensättigung wurde berücksichtigt.

Kalkung: bei Ca+Mg-Basensättigung > 80% und negativem Karbonattest wird Kopfkalkung in die Kultur von ca. 100 kg Ca/ha empfohlen.
Kaliumdüngung: bei Ca+Mg-Basensättigung > 80% und festgestelltem Kaliummangel während des Hauptwachstums wird Kalium-Spätdüngung mit ca. 80 kg K/ha empfohlen. Der Kaliumgehalt der organischen Düngung soll angerechnet werden.

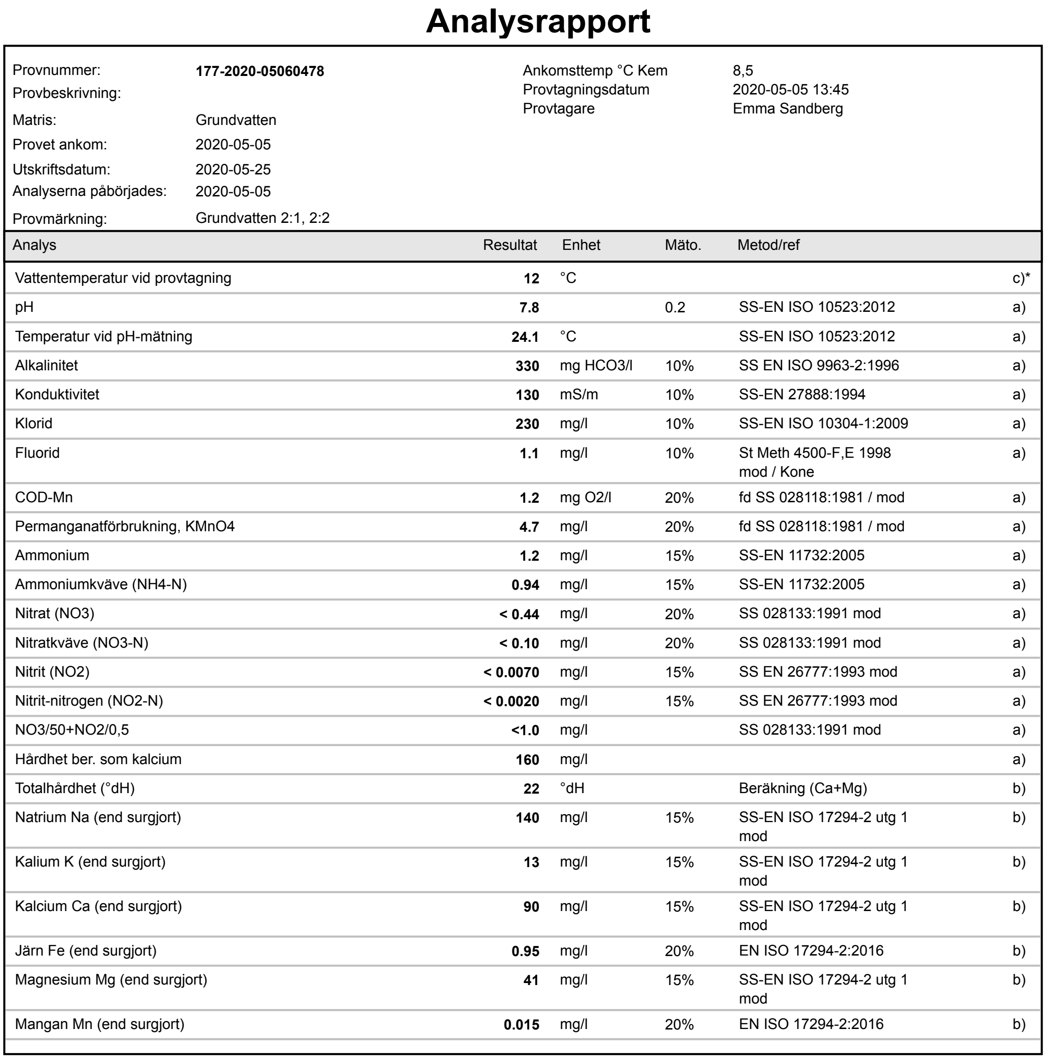
Mikronährstoffe:		**ppm**	**Normalbereich**
B	Wert ppm	1,80	1.2 - 2.4
Fe	Wert ppm	203,00	18 - 189
Mn	Wert ppm	67,30	18 - 70
Cu	Wert ppm	3,90	2.5 - 7.0
Zn	Wert ppm	4,10	4.1 - 10

Priorität:
1 Mg
2 K
3
4
5
6

Dieser Bericht basiert auf der erhaltenen Bodenprobe und ist durch den Absender gekennzeichnet. Das Levende Jord IVS ist nicht verantwortlich für Fehler bei der Probenahme oder Etikettierung.
Analyse in einem nach ISO / IEC 17025: 2017 akkreditierten Labor

Figure A 1: *Albrecht soil analysis carried out on 25th of September 2020.*

Figure A 2*: Fungi (Basidiomycota) on an MC heap.*

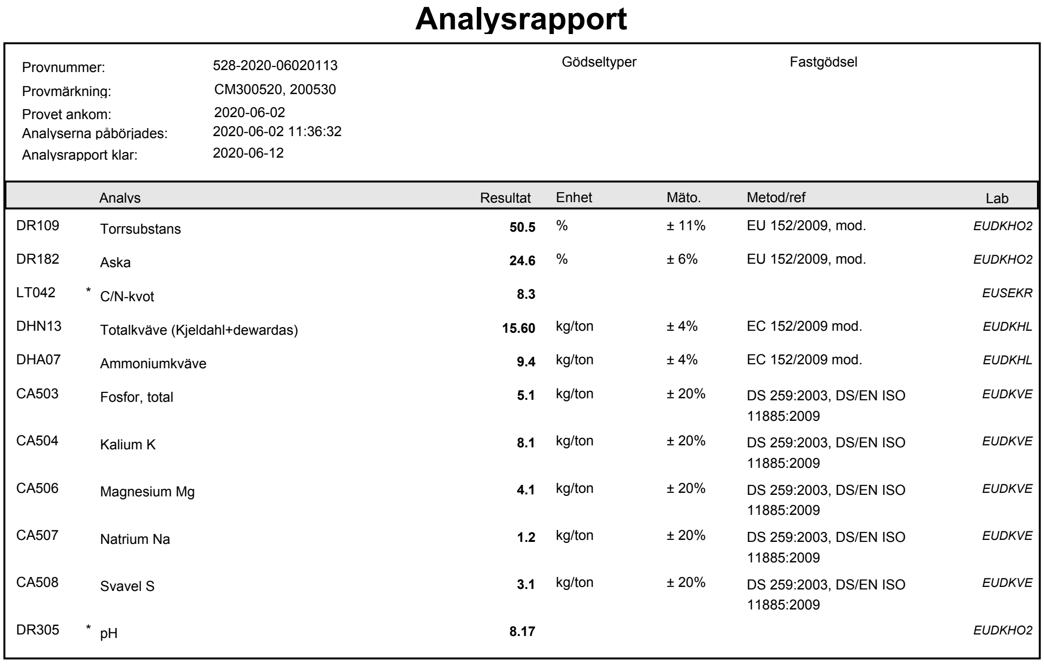


Analysrapport

Provnummer:	**177-2020-05060478**	Ankomsttemp °C Kem	8,5
Provbeskrivning:		Provtagningsdatum	2020-05-05 13:45
Matris:	Grundvatten	Provtagare	Emma Sandberg
Provet ankom:	2020-05-05		
Utskriftsdatum:	2020-05-25		
Analyserna påbörjades:	2020-05-05		
Provmärkning:	Grundvatten 2:1, 2:2		

Analys	Resultat	Enhet	Mäto.	Metod/ref	
Vattentemperatur vid provtagning	**12**	°C			c)*
pH	**7.8**		0.2	SS-EN ISO 10523:2012	a)
Temperatur vid pH-mätning	**24.1**	°C		SS-EN ISO 10523:2012	a)
Alkalinitet	**330**	mg HCO3/l	10%	SS EN ISO 9963-2:1996	a)
Konduktivitet	**130**	mS/m	10%	SS-EN 27888:1994	a)
Klorid	**230**	mg/l	10%	SS-EN ISO 10304-1:2009	a)
Fluorid	**1.1**	mg/l	10%	St Meth 4500-F,E 1998 mod / Kone	a)
COD-Mn	**1.2**	mg O2/l	20%	fd SS 028118:1981 / mod	a)
Permanganatförbrukning, KMnO4	**4.7**	mg/l	20%	fd SS 028118:1981 / mod	a)
Ammonium	**1.2**	mg/l	15%	SS-EN 11732:2005	a)
Ammoniumkväve (NH4-N)	**0.94**	mg/l	15%	SS-EN 11732:2005	a)
Nitrat (NO3)	**< 0.44**	mg/l	20%	SS 028133:1991 mod	a)
Nitratkväve (NO3-N)	**< 0.10**	mg/l	20%	SS 028133:1991 mod	a)
Nitrit (NO2)	**< 0.0070**	mg/l	15%	SS EN 26777:1993 mod	a)
Nitrit-nitrogen (NO2-N)	**< 0.0020**	mg/l	15%	SS EN 26777:1993 mod	a)
NO3/50+NO2/0,5	**<1.0**	mg/l		SS 028133:1991 mod	a)
Hårdhet ber. som kalcium	**160**	mg/l			a)
Totalhårdhet (°dH)	**22**	°dH		Beräkning (Ca+Mg)	b)
Natrium Na (end surgjort)	**140**	mg/l	15%	SS-EN ISO 17294-2 utg 1 mod	b)
Kalium K (end surgjort)	**13**	mg/l	15%	SS-EN ISO 17294-2 utg 1 mod	b)
Kalcium Ca (end surgjort)	**90**	mg/l	15%	SS-EN ISO 17294-2 utg 1 mod	b)
Järn Fe (end surgjort)	**0.95**	mg/l	20%	EN ISO 17294-2:2016	b)
Magnesium Mg (end surgjort)	**41**	mg/l	15%	SS-EN ISO 17294-2 utg 1 mod	b)
Mangan Mn (end surgjort)	**0.015**	mg/l	20%	EN ISO 17294-2:2016	b)

Figure A 3*: Groundwater analysis results from the laboratory Eurofins carried out on 5th of May 2020 on the water which was used for moistening the substrates and producing the hay infusion.*

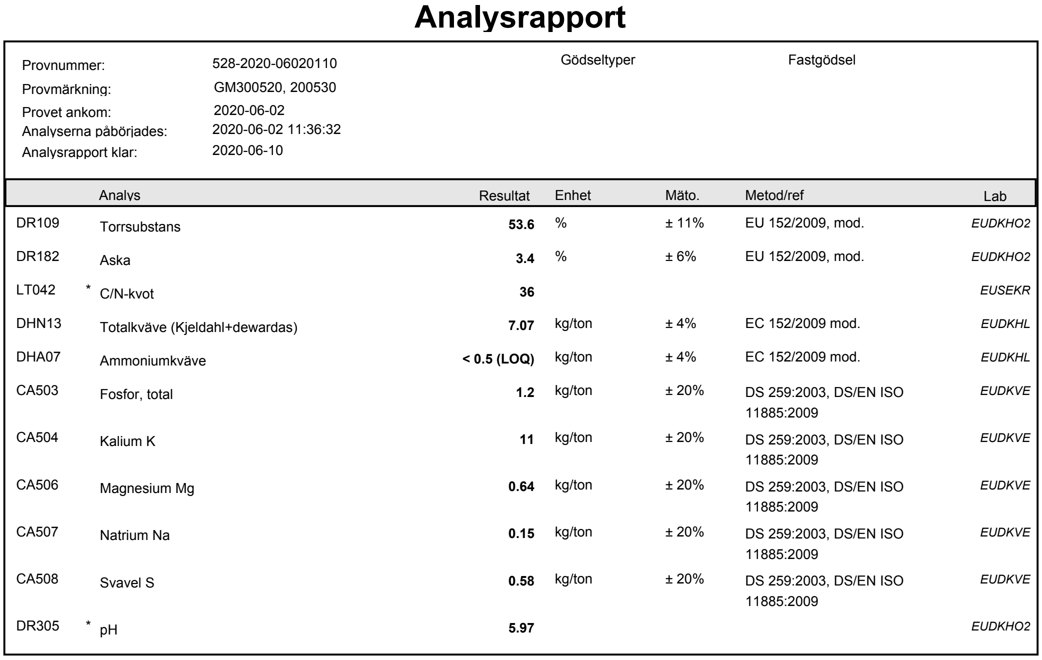


Analysrapport

Provnummer: 528-2020-06020113
Provmärkning: CM300520, 200530
Provet ankom: 2020-06-02
Analyserna påbörjades: 2020-06-02 11:36:32
Analysrapport klar: 2020-06-12
Gödseltyper Fastgödsel

		Analys	Resultat	Enhet	Mäto.	Metod/ref	Lab
DR109		Torrsubstans	**50.5**	%	± 11%	EU 152/2009, mod.	*EUDKHO2*
DR182		Aska	**24.6**	%	± 6%	EU 152/2009, mod.	*EUDKHO2*
LT042	*	C/N-kvot	**8.3**				*EUSEKR*
DHN13		Totalkväve (Kjeldahl+dewardas)	**15.60**	kg/ton	± 4%	EC 152/2009 mod.	*EUDKHL*
DHA07		Ammoniumkväve	**9.4**	kg/ton	± 4%	EC 152/2009 mod.	*EUDKHL*
CA503		Fosfor, total	**5.1**	kg/ton	± 20%	DS 259:2003, DS/EN ISO 11885:2009	*EUDKVE*
CA504		Kalium K	**8.1**	kg/ton	± 20%	DS 259:2003, DS/EN ISO 11885:2009	*EUDKVE*
CA506		Magnesium Mg	**4.1**	kg/ton	± 20%	DS 259:2003, DS/EN ISO 11885:2009	*EUDKVE*
CA507		Natrium Na	**1.2**	kg/ton	± 20%	DS 259:2003, DS/EN ISO 11885:2009	*EUDKVE*
CA508		Svavel S	**3.1**	kg/ton	± 20%	DS 259:2003, DS/EN ISO 11885:2009	*EUDKVE*
DR305	*	pH	**8.17**				*EUDKHO2*

Figure A 4: *Analysis result of chicken manure (CM) carried out at Eurofins on 2nd of June 2020.*

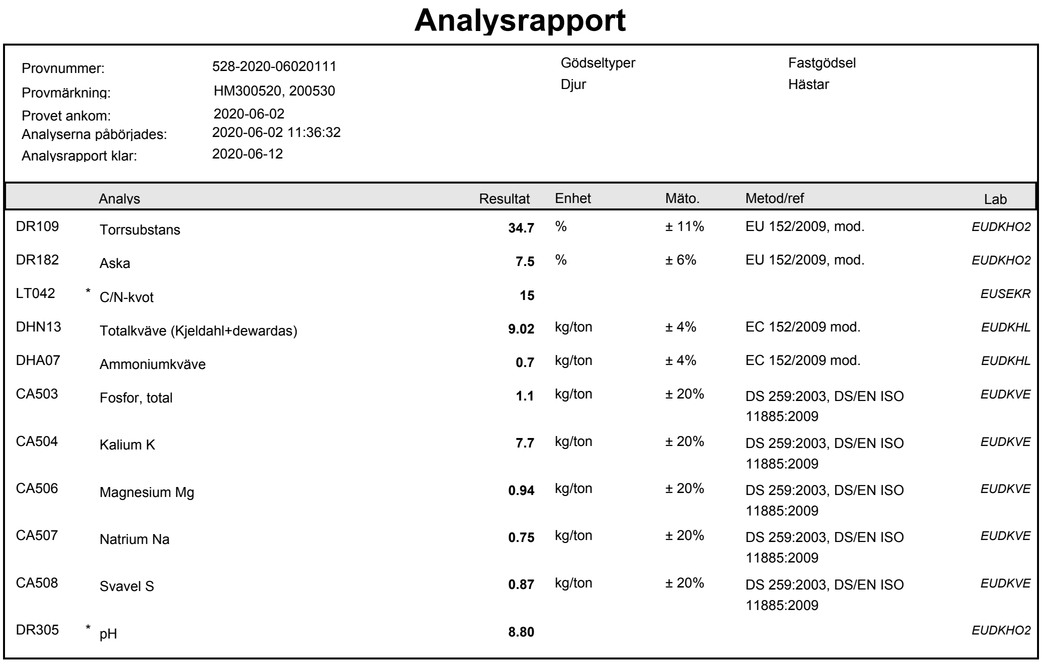


Analysrapport

Provnummer: 528-2020-06020110
Provmärkning: GM300520, 200530
Provet ankom: 2020-06-02
Analyserna påbörjades: 2020-06-02 11:36:32
Analysrapport klar: 2020-06-10
Gödseltyper Fastgödsel

		Analys	Resultat	Enhet	Mäto.	Metod/ref	Lab
DR109		Torrsubstans	**53.6**	%	± 11%	EU 152/2009, mod.	*EUDKHO2*
DR182		Aska	**3.4**	%	± 6%	EU 152/2009, mod.	*EUDKHO2*
LT042	*	C/N-kvot	**36**				*EUSEKR*
DHN13		Totalkväve (Kjeldahl+dewardas)	**7.07**	kg/ton	± 4%	EC 152/2009 mod.	*EUDKHL*
DHA07		Ammoniumkväve	**< 0.5 (LOQ)**	kg/ton	± 4%	EC 152/2009 mod.	*EUDKHL*
CA503		Fosfor, total	**1.2**	kg/ton	± 20%	DS 259:2003, DS/EN ISO 11885:2009	*EUDKVE*
CA504		Kalium K	**11**	kg/ton	± 20%	DS 259:2003, DS/EN ISO 11885:2009	*EUDKVE*
CA506		Magnesium Mg	**0.64**	kg/ton	± 20%	DS 259:2003, DS/EN ISO 11885:2009	*EUDKVE*
CA507		Natrium Na	**0.15**	kg/ton	± 20%	DS 259:2003, DS/EN ISO 11885:2009	*EUDKVE*
CA508		Svavel S	**0.58**	kg/ton	± 20%	DS 259:2003, DS/EN ISO 11885:2009	*EUDKVE*
DR305	*	pH	**5.97**				*EUDKHO2*

Figure A 5: *Analysis result of green manure (GM) carried out at Eurofins on 2nd of June 2020.*



Analysrapport

Provnummer:	528-2020-06020111	Gödseltyper	Fastgödsel
Provmärkning:	HM300520, 200530	Djur	Hästar
Provet ankom:	2020-06-02		
Analyserna påbörjades:	2020-06-02 11:36:32		
Analysrapport klar:	2020-06-12		

	Analys	Resultat	Enhet	Mäto.	Metod/ref	Lab
DR109	Torrsubstans	**34.7**	%	± 11%	EU 152/2009, mod.	*EUDKHO2*
DR182	Aska	**7.5**	%	± 6%	EU 152/2009, mod.	*EUDKHO2*
LT042	* C/N-kvot	**15**				*EUSEKR*
DHN13	Totalkväve (Kjeldahl+dewardas)	**9.02**	kg/ton	± 4%	EC 152/2009 mod.	*EUDKHL*
DHA07	Ammoniumkväve	**0.7**	kg/ton	± 4%	EC 152/2009 mod.	*EUDKHL*
CA503	Fosfor, total	**1.1**	kg/ton	± 20%	DS 259:2003, DS/EN ISO 11885:2009	*EUDKVE*
CA504	Kalium K	**7.7**	kg/ton	± 20%	DS 259:2003, DS/EN ISO 11885:2009	*EUDKVE*
CA506	Magnesium Mg	**0.94**	kg/ton	± 20%	DS 259:2003, DS/EN ISO 11885:2009	*EUDKVE*
CA507	Natrium Na	**0.75**	kg/ton	± 20%	DS 259:2003, DS/EN ISO 11885:2009	*EUDKVE*
CA508	Svavel S	**0.87**	kg/ton	± 20%	DS 259:2003, DS/EN ISO 11885:2009	*EUDKVE*
DR305	* pH	**8.80**				*EUDKHO2*

Figure A 6: *Analysis result of horse manure (HM) carried out at Eurofins on 2nd of June 2020*

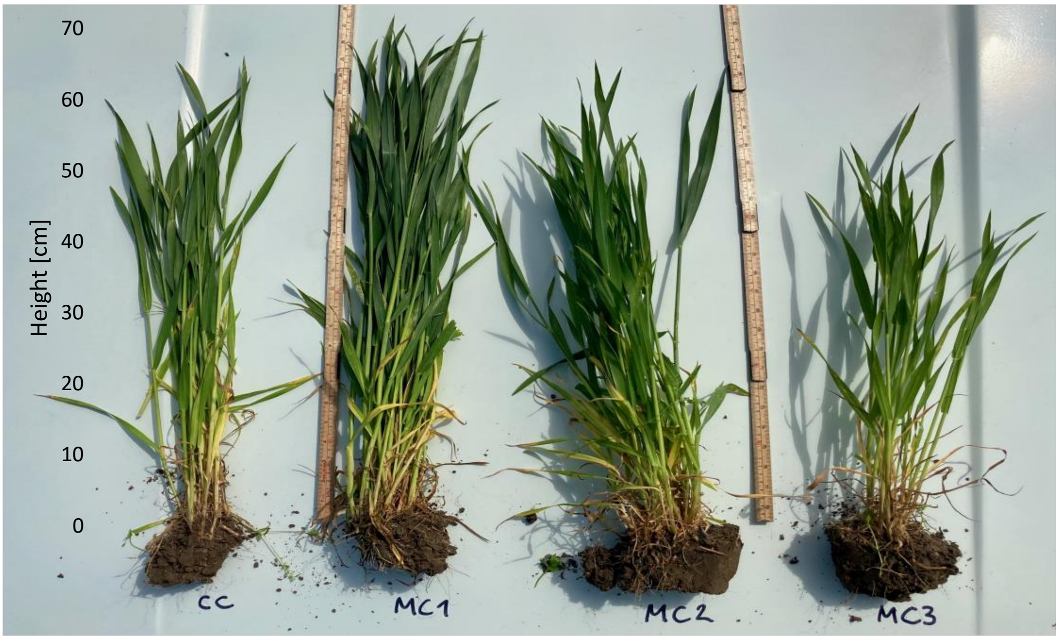


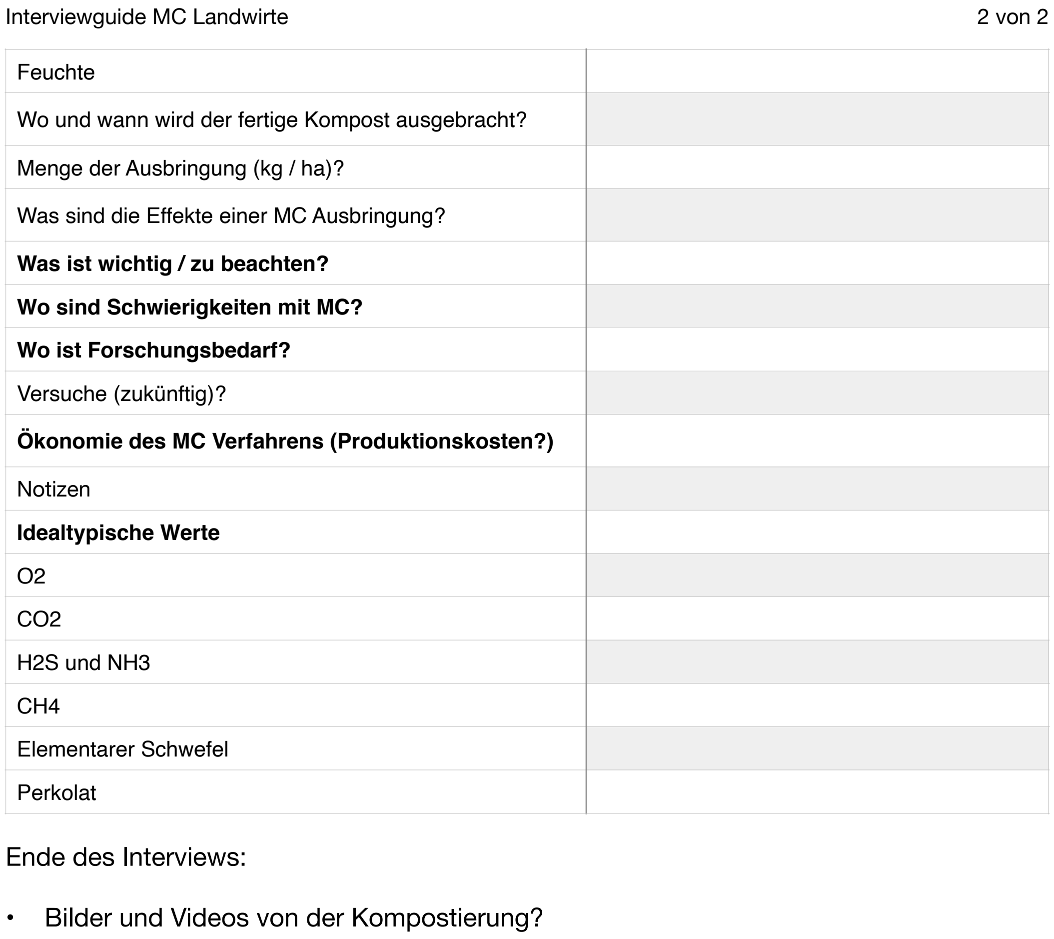
Figure A 7: *Winter wheat (WW) plant height [cm] from plots with 20 Mg ha^{-1} of compost application of the treatments CC and MC1-3(in this order left to right) on 25th of May 2021.*

Interviewguide MC Landwirte 1 von 2

Betrieb: InterviewpartnerIn: Ort:
Datum: Beginn des Interviews:
Ort und Art des Interviews:

- Hinweis zur unterstützenden **Audioaufzeichnung** und zum **Vorgehen mit Rücksprache zur Zusammenfassung**
- Hinweis zur **Verwendung der gemachten Angaben** und Frage nach **Anonymität**

Standortbeschreibung	
Ort der Kompostierung	
Höhe ü.M.	
Jahresdurchschnitts-Niederschlag	
Jahresdurchschnitts-Temperatur	
Betriebstyp und Schwerpunkte, Eckdaten	
Was ist die Motivation für landwirtschaftliche Kompostierung?	
Welche Erfahrungen wurden bisher mit Kompostierung gemacht (verschiedene Methoden)?	
Motivation, mit MC zu arbeiten? Wieso ist MC geeignet für landwirtschaftliche Kompostierung?	
Woher von MC erfahren?	
Seit wann wird MC-Verfahren praktiziert?	
Ausgangssubstrate	
Ablauf der Kompostierung	
Dauer der Kompostierung	
Maschinelle Ausstattung	
Wenden / Mischen / Umsetzen	
Idealer Zeitpunkt zum Aufsetzen	
Standort (Wind, Sonne, Ausrichtung)	
Untergrund	
Form	
Größe	
Oberfläche	
Welche Parameter werden gemessen? (Prozesskontrolle)	
Idealer Temperaturbereich (gemessen in welcher Tiefe?)	
Temperaturentwicklung	
C / N Verhältnis	



Interviewguide MC Landwirte

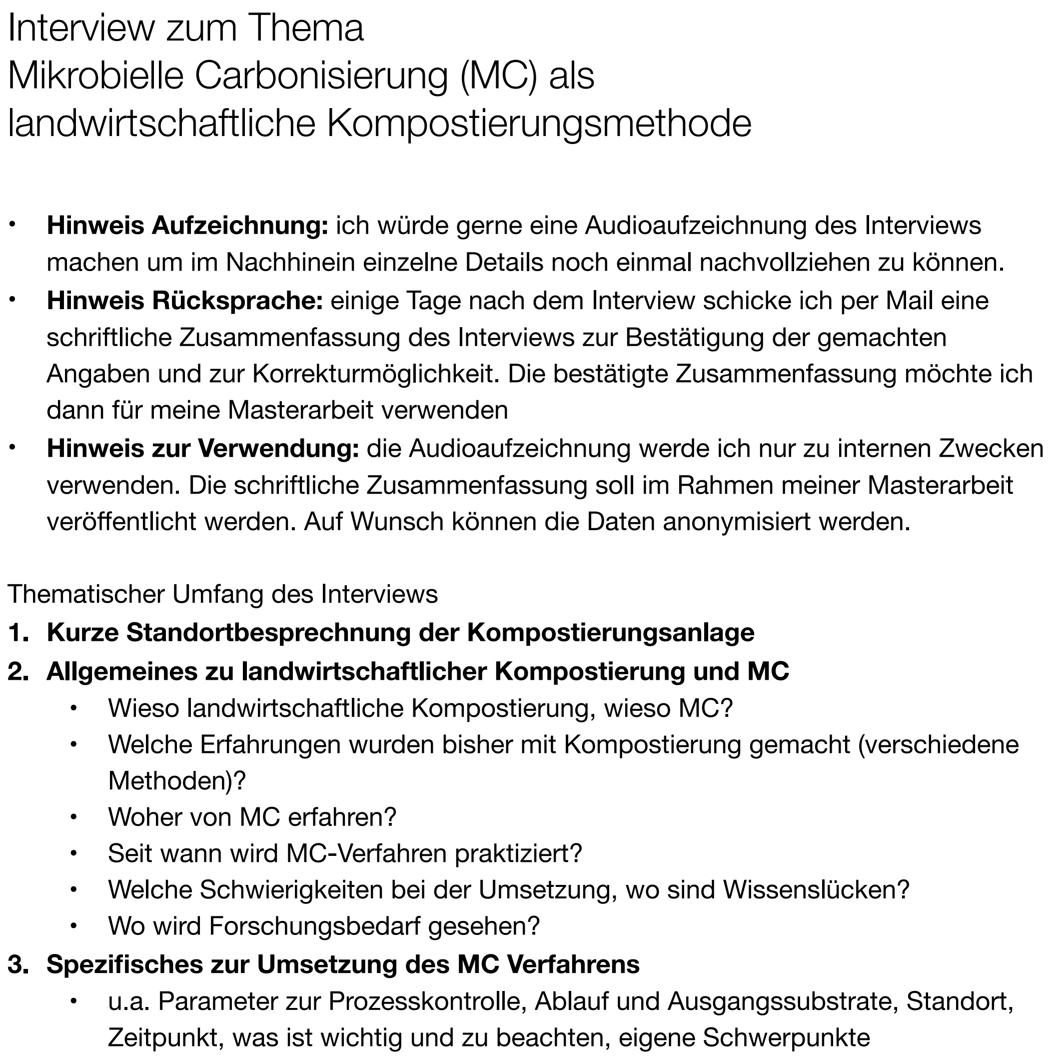
2 von 2

Feuchte	
Wo und wann wird der fertige Kompost ausgebracht?	
Menge der Ausbringung (kg / ha)?	
Was sind die Effekte einer MC Ausbringung?	
Was ist wichtig / zu beachten?	
Wo sind Schwierigkeiten mit MC?	
Wo ist Forschungsbedarf?	
Versuche (zukünftig)?	
Ökonomie des MC Verfahrens (Produktionskosten?)	
Notizen	
Idealtypische Werte	
O_2	
CO_2	
H_2S und NH_3	
CH_4	
Elementarer Schwefel	
Perkolat	

Ende des Interviews:

- Bilder und Videos von der Kompostierung?

Figure A 8: *Interview guide used for conducting the farmers' interviews (condensed representation).*



Interview zum Thema Mikrobielle Carbonisierung (MC) als landwirtschaftliche Kompostierungsmethode

- **Hinweis Aufzeichnung:** ich würde gerne eine Audioaufzeichnung des Interviews machen um im Nachhinein einzelne Details noch einmal nachvollziehen zu können.
- **Hinweis Rücksprache:** einige Tage nach dem Interview schicke ich per Mail eine schriftliche Zusammenfassung des Interviews zur Bestätigung der gemachten Angaben und zur Korrekturmöglichkeit. Die bestätigte Zusammenfassung möchte ich dann für meine Masterarbeit verwenden
- **Hinweis zur Verwendung:** die Audioaufzeichnung werde ich nur zu internen Zwecken verwenden. Die schriftliche Zusammenfassung soll im Rahmen meiner Masterarbeit veröffentlicht werden. Auf Wunsch können die Daten anonymisiert werden.

Thematischer Umfang des Interviews

1. **Kurze Standortbesprechnung der Kompostierungsanlage**
2. **Allgemeines zu landwirtschaftlicher Kompostierung und MC**
   - Wieso landwirtschaftliche Kompostierung, wieso MC?
   - Welche Erfahrungen wurden bisher mit Kompostierung gemacht (verschiedene Methoden)?
   - Woher von MC erfahren?
   - Seit wann wird MC-Verfahren praktiziert?
   - Welche Schwierigkeiten bei der Umsetzung, wo sind Wissenslücken?
   - Wo wird Forschungsbedarf gesehen?
3. **Spezifisches zur Umsetzung des MC Verfahrens**
   - u.a. Parameter zur Prozesskontrolle, Ablauf und Ausgangssubstrate, Standort, Zeitpunkt, was ist wichtig und zu beachten, eigene Schwerpunkte

Figure A 9: *Introducing document sent to the interviewed farmers in advance of the interview for introducing them to the content and the individually focussed interview (TIFI) method.*

Table A 10: *Mean values of chamber air measured with Dräger X-am® 7000 and carried out after the regular emission (EM) samplings.*

		11.06.	**14.06.**	**16.06.**	**24.06.**	**26.06.**	**29.06.**	**02.07.**	**05.07.**	**08.07.**	**12.07.**	**16.07.**	**20.07.**	**24.07.**	**29.07.**	**04.07.**	**23.08.**	**Sum**	**Mean value**
CH_4	**CC**	0.0	0.0	0.1	0.0	0.0	0.0	0.0	0.1	0.2	0.4	0.3	0.0	0.0	0.0	0.0	0.0	1.13	0.07
	MC2	0.3	0.3	0.3	0.3	0.1	0.1	0.3	0.0	0.3	0.4	0.4	0.4	0.3	0.1	0.3	0.0	3.93	0.25
	MC1	0.2	0.0	0.2	0.1	0.1	0.2	0.1	0.0	0.3	0.3	0.3	0.3	0.3	0.2	0.2	0.1	2.93	0.18
CO_2	**CC**	1.0	1.1	1.7	0.9	1.2	0.9	0.7	0.6	1.3	0.7	0.9	0.7	1.0	0.7	0.7	0.4	14.53	0.91
	MC2	1.2	1.1	1.3	1.1	1.0	0.6	1.0	0.4	0.9	0.8	0.9	0.7	0.8	0.5	0.7	0.3	13.33	0.83
	MC1	1.1	0.9	1.0	0.9	0.9	0.7	0.8	0.1	0.8	0.7	0.6	0.5	0.7	0.3	0.7	0.3	11.03	0.69
O_2	**CC**	18.6	19.7	19.1	19.4	19.4	19.4	19.8	19.7	19.2	19.7	19.4	19.7	19.4	19.5	19.9	20.0	311.90	19.49
	MC2	19.2	19.6	19.4	19.6	19.8	20.0	19.6	20.0	19.6	19.9	19.6	19.8	19.7	19.9	19.8	20.4	315.97	19.75
	MC1	19.3	20.3	19.6	19.8	20.1	20.0	19.9	20.2	19.8	20.0	19.5	20.2	19.8	20.0	20.0	20.2	318.75	19.92
H_2S	**CC**	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.2	1.0	2.3	1.7	3.0	2.5	2.8	0.5	0.0	14.00	0.88
	MC2	0.0	0.0	0.0	0.0	0.4	0.0	0.0	0.5	1.7	3.1	4.6	10.3	10.2	12.4	18.7	4.0	65.83	4.11
	MC1	0.0	0.0	0.0	1.1	1.6	1.3	1.0	1.0	3.1	5.8	11.1	11.9	20.0	22.3	26.5	7.2	113.90	7.12
NH_3	**CC**	4.0	5.7	4.3	18.7	26.0	13.3	34.7	87.0	148.0	33.0	59.7	17.3	35.7	36.3	12.0	69.7	605.33	37.83
	MC2	3.7	2.3	8.0	-0.7	14.7	16.3	11.3	55.3	45.3	23.7	18.0	12.0	17.0	28.3	6.0	46.7	308.00	19.25
	MC1	3.7	5.0	9.3	1.7	-1.7	11.7	8.3	34.3	24.7	23.0	14.3	12.0	10.7	19.3	0.0	31.7	208.00	13.00

Table A 11: *Significant correlations of pore gases (PG) and emissions (EM) of MC1 & 2. Significance values, according to the Spearman test, are indicated by superscript stars. Number of correlated pairs is 18 for all correlations.*

	CH_4 0.65 m	**CH_4 1.5 m**	**CO_2 0.65 m**	**CO_2 1.5 m**	**O_2 0.65 m**	**H_2S 0.65 m**	**H_2S 1.5 m**	**NH_3 0.65 m**	**N_2O EM**
CO_2 0.65 m	MC1: .575* MC2: .690**								
CO_2 1.5 m			MC1: .678** MC2: .688**						
O_2 0.65 m	MC2: -.555*	MC1: .469*	MC1: -.791** MC2: -.934**	MC2: -.720**					
H_2S 0.65 m	MC1: .498* MC2: .502*		MC1: .937** MC2: .733**	MC1: .626** MC2: .790**	MC1: -.766** MC2: -.699**				
H_2S 1.5 m	MC2: .500*		MC2: .576*	MC1: .476* MC2: .696**	MC2: -.503*	MC2: .846**			
NH_3 0.65 m			MC1: .779** MC2: .670**	MC1: .727** MC2: .840**	MC2: -.699**	MC1: .739** MC2: .918**	MC2: .740**		
NH_3 1.5 m			MC2: .554*	MC2: .755**	MC2: -.504*	MC2: .864**	MC1: .856** MC2: .968**	MC2: .818**	
N_2O EM			MC1: -.775** MC2: -.635**	MC1: -.737** MC2: -.721**	MC1: .600** MC2: .714**	MC1: -.731**		MC1: -.799** MC2: -.549*	
CH_4 EM									MC1: .552*
CO_2 EM			MC1: .821** MC2: .570*	MC2: .608**	MC1: -.831** MC2: -.653**	MC1: .831**		MC1: .566*	MC1: -.707** MC2: -.765**

*. Correlation is significant at the 0.05 level (2-tailed).

**. Correlation is significant at the 0.01 level (2-tailed).

N = 18 for all correlations. EM = Emissions

Table A 12: *Significant correlations of pore gas concentrations (PGC) before (BA) and after (AA) aeration happenings and emissions (EM) of CC. Significance values, according to the Spearman test, are indicated by superscript stars and the number of correlated pairs is indicated by superscript letters a-f.*

	CH_4	**CO_2**	**CO_2 AA**	**O_2**	**O_2 AA**	**H_2S**
CO_2	.615^{**a}					
CO_2 AA	.881^{**d}	.714^{*d}				
O_2		-.575^{*a}				
O_2 AA	-.850^{**d}		-.934^{**d}			
H_2S		.852^{**a}	.723^{*d}	-.636^{**a}		
NH_3		.643^{**c}				.813^{**c}
N_2O EM				.690^{**a}		
CH_4 EM	.582^{*a}	.537^{*a}	.786^{*d}		-.850^{**d}	
CO_2 EM				-.667^{**a}		

**. Correlation is significant at the 0.01 level (2-tailed).

*. Correlation is significant at the 0.05 level (2-tailed).

^{a}. N = 18, ^{b}. N = 16, ^{c}. N = 15, ^{d}. N = 8, ^{e}. N = 7, ^{f}. N = 5

AA = measurement 1-67 min (in average: 18 min) after an aeration happening. EM = Emissions.

Table A 13: *Compost substrate properties and carbon (C) fractions, according to Van Soest, of MC3 after composting on 22.09.20.*

	MC3
DM [%]	52 / 49^{b}
Ash [% FM]	33
Ash [% DM] ^{c}	69
pH	8.8
P/N	0.2
C/N	11 / 14^{a}
C_{-tot} [% DM] ^{a}	11
N_{-tot} [kg Mg^{-1} DM]	9 / 8^{a}
NH_4-N [kg Mg^{-1} DM]	1.9
P [kg Mg^{-1} DM]	1.8
K [kg Mg^{-1} DM]	5.6
Mg [kg Mg^{-1} DM]	1.3
Na [kg Mg^{-1} DM]	0.7
S [kg Mg^{-1} DM]	1.2
Van Soest analysis of C- fractions (% of ash-free DM)	
Fibres insoluble^{c} [%]	68.7
Fibres soluble^{c} [%]	9.4
Soluble non-fibres^{c} [%]	37.6
Soluble components^{c} [%]	47.0
Hemicellulose^{c} [%]	15.2
Cellulose^{c} [%]	19.7
Lignin^{c} [%]	18.1

^{a} Results from CU, ^{b} Results from SLU, ^{c} results from Artemis, other results are from Eurofins. * Calculated average of MC1 & 2. FM: fresh matter, DM: dry matter.

Practice factsheet

On-farm composting using the reductive composting method Microbial Carbonisation (MC)

Release date: January 2022
Author: Ludwig Stephan, correspondence: ludwigs@mail.de

Agricultural problems, such as declining soil fertility, nutrient losses from cropping systems and greenhouse gas (GHG) emissions, that exacerbate the threat of climate change, require solutions for a more sustainable way of recycling nutrients (IPES-Food 2016). The use of available biomasses and manures through on-farm composting can possibly contribute to reduce the extent of such problems.

This fact sheet summarises the most practice-relevant key findings of the latest study on the reductive composting method Microbial Carbonisation (MC) (Stephan 2022). During this study, field trials were conducted, to evaluate different aspects of the method. A diverse data collection was carried out including substrate, soil, emission, and pore gas concentration measurements as well as records of the machinery use. In addition, interviews were conducted, with farmers already using MC in practice, to gain a better insight into its practical application.

The factsheet is intended to provide farmers with the advantages and disadvantages of MC composting to facilitate the decision as to whether this method is practicable on the respective farm.

What is the Microbial Carbonisation?

MC can be understood as a microbial transformation process of biomasses under conditions of limited oxygen (anoxic) and moderate temperatures (mesophilic) into a compost substrate rich in plant-nutrients and carbon (Wonschik 2017; Stephan 2022). One of the most obvious differences to CC is that, due to the lower oxygen demand, mechanical aeration by turning the windrow is not necessary.

Figure 1: Setting up an MC heap with a manure spreader. © Stephan, L.

Fact-box 1: How to do MC composting on the farm

(Based on Witte n.d. and the farmers' statements from Stephan 2020)

1. Collection of the materials on the farm, preferably as fresh as possible, particle sizes should be below 6 cm.
2. Thorough mixing of the materials with the shovel of a wheel loader, when all materials are available in the right proportion – 1/3 of the material should be protein-rich and 2/3 lignin-rich (see fact-box 3).
3. The substrate mix is left in loose heaps for maceration (rapid reproduction of microbes, even moistening of the substrate and cell wall destruction) until temperatures approach 50 – 60 °C.
4. Trapezoidal MC heaps are setup with the wheel loader or manure spreader. The heap should be loose with plenty of pore-space for gas-exchange.
5. The surface needs to be gently compacted with the wheel loader shovel and perhaps corrected manually with a hay rake to exclude any additional oxygen input into the heap.
6. The MC process needs to run for at least two months.

Figure 2: Two MC heaps piled against a concrete wall. Left side with compacted surface, right side not yet compacted. © Stephan, L.

A valuable fertiliser

MC substrates were found to contain about 35% more nitrogen (N) and about 30 % more carbon (C) after composting. This is due to possibly higher N and C losses from CC in the form of gaseous emissions and leakage. With most of the C and N from the compost start substrates remaining, MC appears to be promising for use in an RA context with a focus on soil fertility. However, the long-term effects on soil organic matter (SOM) were not investigated in the present study. Emission measurements indicate that some of the N and C delivered to the field by MC compost must also have been emitted there.

A labour-efficient composting method

Applied on an organic arable farm in Sweden, MC proved to be a very cost-efficient composting method. It required less labour than CC and therefore seems particularly suitable for processing and refining larger quantities of biomasses produced on a farm such as manure. The machinery requirement of MC was only one tenth of the more labour-intensive CC process when implemented with common agricultural machinery such as a wheel loader. MC therefore seems to be more feasible with the usual farm machinery. For CC, on the other hand, special machinery for turning the windrows is needed for a good management. By using windrow-turners, even higher efficiencies could be achieved with CC, but this would in turn require additional investments.

Fact-box 2: The key differences of MC and CC

(According to the results from Stephan 2022)

	MC	CC
Total nitrogen (N_{tot}) content [kg t^{-1} DM]	+	–
Ammonium (NH_4-N) content [kg t^{-1} DM]	+	–
Total carbon (C_{tot}) content [% DM]	+	–
Machinery and labour input [h kg^{-1} N]	–	+
GHG emissions during composting [kg $CO_{2\text{-eq}}$ t^{-1}]	–	+
GHG emissions from field application [kg $CO_{2\text{-eq}}$ ha^{-1}]	+	–
Total GHG emissions [$CO_{2\text{-eq}}$ kg^{-1} N]	–	+
Possibilities for adjustments during composting	–	+

"+" means more and "–" means less. DM = dry matter

The tricky question of GHG emissions

First and foremost, the reduced use of machinery in MC is most-likely also associated with lower fossil fuel related emissions than in CC. GHG emissions (carbon dioxide: CO_2, methane: CH_4 and nitrous oxide: N_2O) from composting of MC and CC and the field application of these composts were measured and compared on a $CO_{2\text{-eq}}$ equivalent ($CO_{2\text{-eq}}$) basis. A novelty of this study was that N_2O emissions were measured for the first time on an MC compost. It was found that N_2O emissions during composting were three times lower on MC than on CC. On the other hand, during the first 11 weeks after field application, the N_2O emissions were about 25 % higher in MC.

In relation to a ton (t) of compost substrate, MC showed 30 – 40 % lower GHG emissions during composting, compared to CC. This advantage, however, was offset by 28 – 40 % higher GHG emissions per hectare (ha) in the field during the first 11 weeks after application. Another picture emerges, when emissions are viewed in relation to the N-content of the final compost substrate, which mainly accounts for the fertilisation value. As MC had higher N contents during composting, hence MC emitted less GHG per kg N applied to the field in total (including emissions from composting and the first 11 weeks after application).

In summary, it can unfortunately not clearly be assessed whether MC or CC emitted less GHG in general, and it became apparent how much this assessment depends on the reference value (e. g. t or N). Nevertheless, the high C and N contents of MC substrates seem to bear the risk of higher GHG emissions after field application.

Conclusion

Regarding the high labour efficiency and the possibility of simple implementation with

Fact-box 3: MC composting in a nutshell

(Based on Wonschik 2017; Stephan 2022; Witte n. d.)

Temperature: 40 – 60 °C

Moisture: 40 – 60 % H_2O

Pore gas concentrations:

- O_2: < 1 vol% (after one day)
- CO_2: 30 – 45 vol%
- CH_4: 5 – 45 vol%
- H_2S and NH_3 can be high in the beginning
- High H^+

Duration of composting: minimum two months

Site: paved ground or field border (depending on local fertilisation regulations), walls to lean the heap on can be beneficial

Season: preferably spring and autumn

Input materials: manure, clover-grass and green manure cuttings, hay, residues from seed cleaning and dehulling, wood chips, straw, reed, stone flour …

Required machines: a wheel loader and perhaps a manure spreader

Labour requirement: about 25 m^3 per hour for setting up the heap existing machinery MC can be recommended for on-farm application. Moreover, high N and C contents indicate a good fertilisation value and bear the potential to contribute to increasing SOM. On the other hand, this can also lead to increased emissions in the field, thus there is a need for further research here.

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If you have further questions or need advice on MC, please leave me a message: ludwigs@mail.de.

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